AEOLIAN DUNE FIELDS OF KANSAS AND THEIR RESPONSE TO LATE-QUATERNARY DROUGHT

by

Alan Frederick Halfen

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William C. Johnson, Ph.D. (Chair)

Joel Q.G. Spencer, Ph.D.

Daniel R. Hirmas, Ph.D.

Nathaniel A. Brunsell, Ph.D.

Stephen T. Hasiotis, Ph.D.

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The Dissertation Committee for Alan Frederick Halfen certifies that
this is the approved version of the following dissertation:

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William C. Johnson, Ph.D. (Chair)

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ABSTRACT

Aeolian dune fields are ubiquitous features of the North American Great Plains, and contained within their stratigraphy are important records of changes in prehistoric climate. Using absolute dating techniques, researchers can determine the timing of past dune field activity, which in many cases, is the result of drought. Based on a drought-aeolian activity relationship, the timing of past dune activity can, therefore, be used as a proxy for prehistoric drought. This dissertation presents three chronologies of dune activity from understudied dune fields in Kansas. Each chronology has been established using new optically stimulated luminescence ages, which in total account for nearly 25% of the total luminescence ages reported from all U.S. Great Plains dune fields. In general, dune activity in Kansas is coeval with that recorded throughout the Great Plains, but, in particular, Kansas dunes were active during defined periods of drought recorded in other regional proxies.

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Dedicated to Alice and Fred

In Memory of Bill Schnormeier

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INTRODUCTION

1.1. Problem statement

Barren plains, blowing sand, and skies darkened with silt and dust are vivid images of the North American Great Plains during the 1930's Dust Bowl, a time when drought conditions, coupled with poor agricultural practices, resulted in the region-wide destabilization of soils and the subsequent aeolian sedimentation of those sediments. Beyond the agricultural, societal, and financial impacts of the 1930's Dust Bowl, the period also resulted in a scarred landscape in which more than 75% of the topsoil was eroded away by the wind (Hornbeck, 2009). Despite poor farming practices, which contributed to the extensive soil erosion in the 1930s, the underlying cause was spatially extensive and long-duration drought.

Historical droughts are common place on the North American Great Plains, with several ominous droughts recorded during the last century alone, including most recently the ongoing drought since 2010, which has impacted most of the southwestern United States, Great Plains, and Midwest. Considering the propensity of historic Great Plains droughts, it is logical to assume that drought will continue to impact the Great Plains into the future. This is particularly true given current changes in regional climate. Climate models have predicted that if CO_2 and other greenhouse gas emissions continue to increase as projected, by A.D. 2100 temperatures could increase in the Great Plains by up to 4°C, which would result in significantly less precipitation (Brunsell et at., 2010; GCC, 2012). With less precipitation, effective soil moisture will decrease and vegetation will once again wither, exposing soils to the erosive force of the wind.

Although many historical droughts of the Great Plains were geographically extensive and were several years in duration, they pale in comparison to prehistoric Great Plains droughts, which occurred regularly throughout the late Quaternary. These prehistoric droughts, termed “megadroughts,” were geographically extensive droughts of greater severity and longer duration than the worst recorded historic droughts.

Great Plains dune fields are important proxies of pehistoric megadroughts because they are 1) responsive to changes in climate, especially drought, and record these changes within their stratigraphy; 2) easily datable using luminescence techniques, providing a reliable chronology of these climatic events; and 3) abundant throughout the Great Plains, whereas other drought proxies, such as fossil pollen and tree ring reconstructions, are not. Climatic records are extracted from dune fields by dating episodes of dune activity and dune stability, which are expressed within a dune’s stratigraphy as aeolian deposition and weakly developed soils, respectively.

Throughout the late Quaternary, climatic fluctuations have forced several periods of aridity and aeolian sedimentation in the Great Plains, some of which have been identified by researchers as megadroughts. Despite identifying these droughts, the exact timing and spatial extent of these events has been difficult to reconcile. This is in part because records of dune activity from the Great Plains cannot be linked to every drought documented in other paleoclimatic records, and, in some cases, neighboring dune fields record different landscape responses to the same drought conditions. These problems, which have traditionally been attributed to dating errors or simply to the complex nature of dune fields, have made it difficult to characterize region-wide drought patterns and to link these patterns to continental-scale forcing mechanisms. An under-appreciated problem with correlating drought across the Great Plains is that many dune fields are lacking in chronological data, essentially making regional comparisons of dune activity impossible. This is especially true for the central Great Plains, specifically Kansas, where, despite having the over 16,000 km^2 of sand dunes, the current number of chronologies supporting prehistoric dune activity is severely limited.

Bearing the above in mind, this dissertation research aims to reconstruct the timing, severity, and geographical extent of late-Quaternary megadroughts in Kansas (i.e., the central Great Plains) by investigating three aeolian dune fields spread across the state. This research will 1) substantially increase the number of dune activation ages from the central Great Plains, 2) advance our understanding of past megadroughts in Kansas, and 3) provide a new foundation from which future regional studies can better link Great Plains landscape response to the large-scale atmospheric changes responsible for regional drought.

1.2. Research significance

This dissertation research is significant because our understanding of prehistoric megadrought is paramount to predicting and planning for future droughts. Droughts have staggering impacts on infrastructure and agriculture, costing the United States between $6 and $8 billion dollars annually (Sivakumar, 2011). Future droughts, especially those impacting the Great Plains, will likely have far greater consequences given the current agricultural importance of the region. Data from this dissertation will help refine climate models, which will then better predict the timing and severity of future Great Plains drought.

In addition, this research will provide new ages of dune field activity from Kansas, an area of the Great Plains that is relatively understudied. Until recently, most dune field research has been focused on Canada (e.g., Wolfe et al., 2002a; 2006; 2009), Nebraska (e.g., Goble et al., 2004; Mason et al., 2004; Forman et al., 2005; Miao et al., 2007a), the Southern High Plains (e.g., Holliday, 2001; Holliday et al., 2008), and Colorado (e.g., Muhs and Maat, 1993; Madole, 1995; Muhs et al., 1996; Forman et al., 2001; Clarke and Rendell, 2003). Only five studies have provided any chronological control of dune activity from dune fields in Kansas: the Great Bend Sand Prairie (Arbogast, 1996; Arbogast and Johnson, 1998), the Arkansas River dunes (Forman et al., 2008), the Abilene dunes (Hanson et al., 2010), and the Cimarron Bend dunes (Werner et al., 2011). The ages provided in these reports present a reasonable beginning to a robust data set, but together, account for only ~40 ages. For comparison, the Nebraska Sand Hills data set alone has over 350 ages.

Lastly, this research is significant because defining the spatial and temporal patterns of dune activity in Kansas will better help to identify patterns of prehistoric drought in the central Great Plains, which are currently lacking. A better understanding of drought in the central Great Plains will allow for a greater appreciation of drought across the entire region. For example, current drought chronologies of the northern and southern Great Plains do not correlate well, and developing a chronology in the central Great Plains may help explain why correlation is difficult. It may also identify patterns of drought initiation and movement, for example, prehistoric droughts may initiate in the southwest and move northeast, or vise versa. Understanding these patterns also has implications for linking drought to the large-scale atmosphere dynamics responsible for climate change in the Great Plains, which to date are not fully known.

1.3. Organization of this dissertation

This dissertation has been organized into six chapters: this introduction, a review chapter on the dune field chronological studies of the Great Plains, three specific studies focused on dune fields of Kansas, and a summary. The review chapter (Chapter 2) provides a critical review on the history and future of Great Plains dune field activation chronologies, which includes an exhaustive literature review and analysis of past dune field chronological studies. This chapter also includes comprehensive tables of radiocarbon and luminescence ages from all studied Great Plains dune fields, which support the discussion section in Chapter 2 and those throughout the other chapters. A full list of all original and calibrated radiocarbon and luminescence ages from Great Plains dune fields is found in Appendix I. Chapters 3–5 each describe a study from a specific dune field in Kansas, beginning with the Hutchinson dunes in Chapter 3, the Arkansas River dunes in Chapter 4, and the Kansas River dunes in Chapter 5. Chapter 6 summarizes this dissertation and includes bulleted points highlighting the principle conclusions of Chapters 2–5.

Chapter 2

A REVIEW OF GREAT PLAINS DUNE FIELD CHRONOLOGIES

2.1. Introduction

Aeolian dune fields of the North American Great Plains contain an abundance of paleoclimatic information and have provided scientists expansive landscapes from which nearly four decades of geomorphic and paleoclimatic research has been conducted. This research, which has focused primarily on reconstructing the paleohistory of dune and sand sheet activity by dating aeolian stratigraphy, has linked prehistoric dune activation to drought under the assumption that 1) aeolian sedimentation occurs when sediment is abundant and freely available for transport by strong winds (Pye and Tsoar, 1990; Lancaster, 1995; Livingstone and Warren, 1996; Kocurek and Lancaster, 1999), and 2) in the North American Great Plains, changes in sediment availability occur during prolonged drought when vegetation normally covering dune fields is desiccated leaving sand exposed to strong and persistent winds (e.g., Muhs and Maat, 1993; Muhs and Holliday, 1995). Conversely, during mesic conditions, vegetation re-establishes and stabilizes dune fields of the region. (e.g., Muhs and Maat, 1993; Muhs and Holliday, 1995; Wolfe, 1997; Holliday, 2001).

This basic relationship has served as the underlying assumption for most chronological dune studies on the Great Plains, and, although a number of studies provide reliable chronologies, there are still many spatial and temporal issues with correlating dune activity across the region. Many of these issues arise because not all dune fields in the Great Plains have been studied, which creates large spatial gaps in current chronological data sets. In other instances, dune fields have been sampled, but not to the same stratigraphic extent as others, which results in gaps in temporal data. In other cases still, dune field chronologies have produced more questions than answers by highlighting the geomorphic complexities of individual dune fields (e.g., Loope et al., 1995; Wolfe et al., 2007a; Forman et al., 2008; Wolfe and Hugenholtz, 2009; Halfen et al., 2010; Werner et al., 2011). Specifically, these studies have argued that local dune field controls may overprint regional climate signals (e.g., Wolfe et al., 2007a; Forman et al., 2008; Wolfe and Hugenholtz, 2009; Halfen et al., 2010), or that some dune activity may not be directly related to drought, but rather to geomorphic feedbacks from other landscape changes (Werner et al., 2011), early human occupation (Wolfe et al., 2007a), or complex ground-water interactions (e.g., Loope et al., 1995; Mason et al., 2004).

Considering the ubiquity and paleoclimatic important of Great Plains dune fields, they remain an important proxy of late-Quaternary climate. Future studies will need to consider the current spatial and temporal limitations in the existing data sets, especially if these studies attribute dune activity to climate. The aim of this review, therefore, is to 1) summarize the past forty years of Great Plains dune research, particularly that which has derived chronologies of prehistoric dune and sand sheet activity, 2) highlight recognized spatial and temporal patterns of prehistoric dune activity, 3) discuss areas of limited understanding in current chronological data such that future studies can focus on gaps in our current comprehension of spatial and temporal aspects of prehistoric dune activity, and 4) provide a repository for all chronological data from dune fields of the Great Plains, which can be accessed for future studies.

An important component of this review is the age data presented within, which are based on dating techniques that have advanced significantly within the time frame covered by the cited literature. In an effort to avoid confusion, all ages are presented herein as originally reported by individual authors. Ages represented in figures have all been calibrated to years before A.D. 2012, which was necessary to facilitate the visual comparison of age data. All age data presented in this study, including original and calibrated ages, have been tabularized and are available in Appendix I. A few additional chronologies appear within the gray literature (e.g., dissertations, field trip guides, archaeological reports), but those chronologies are not considered here, because the vast majority of ages therein have been reported as part of peer-reviewed sources included in this study's database. Finally, the phrase "dune activity," as referred to in this manuscript, is clarified to encompasses all aeolian sand activity documented in Great Plains dune field studies, including but not limited to dune construction, dune migration, dune deflation, and sand sheet erosion and deposition.

2.2. Publication trends in Great Plains dune research

Prior to the 1970s, studies that dated activation of Great Plains dune fields were few in number, and their assessments on the timing of dune activity were based extensively on dune stratigraphy or morphology rather than on absolute numerical dating. For example, Smith (1940) described a cycle of dune activity and stability in southwestern Kansas based on dune stratigraphy and morphology. He argued that modern prevailing winds could not have created the dune forms present, and, therefore, those morphologies represented prehistoric dune activity. Simonett (1960) used dune morphology and hypothesized wind reconstructions to conclude that dune development in western Kansas occurred in the latest Pleistocene following retreat of the Laurentide Ice Sheet. Smith (1965) used similar interpretations of Simonett (1960) to reach a comparable conclusion about the formation of the Nebraska Sand Hills. Morphology was also used to make early assessments of dune fields in Canada (e.g., David, 1968) and in the Southern High Plains (e.g., Melton 1940; Huffington and Albritton, 1941). These early studies and their geomorphic and chronologic assessments laid the foundation for what would subsequently become a significant body of literature.

Publications presenting absolute dune field chronologies—those numerically derived from radiocarbon (^{14}C) or luminescence dating—emerged in the 1970s, advancing concurrently with the widespread development and implementation of ^{14}C

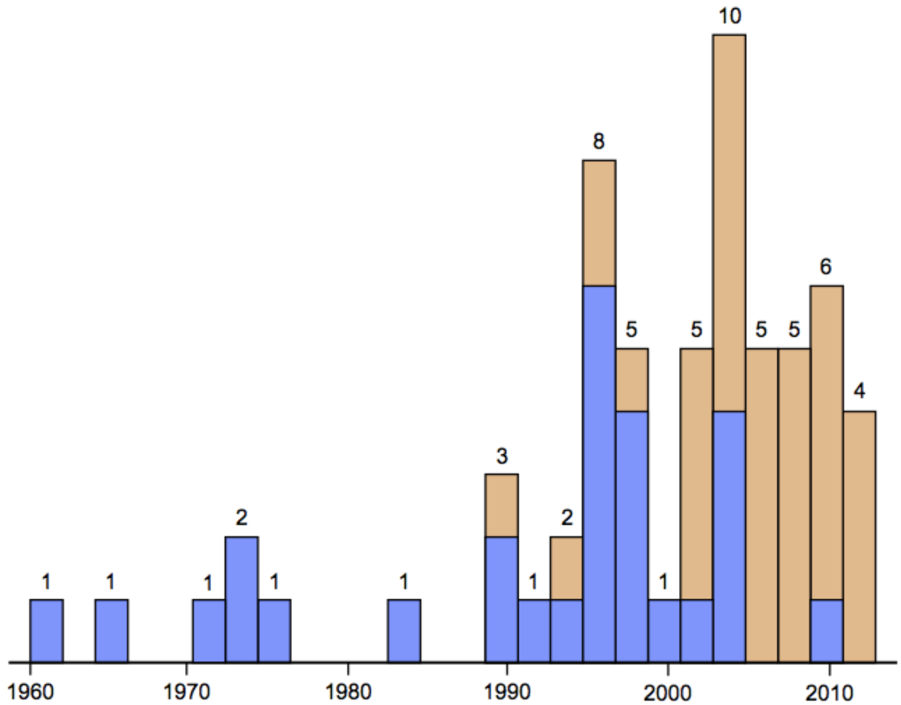


Figure 2.1. Frequency of studies published between AD 1960 and 2012 that provide chronological data on dune activity within and immediately adjacent to the North American Great Plains. Bins are two-year intervals, with the number above the bin indicating the total number of studies. Blue shading (darkest in grayscale) indicates chronologies established using ^{14}C ages; tan shading indicates luminescence-based chronologies.

dating (Fig. 2.1). The first studies to employ ^{14}C dating in development of a dune chronology did so by dating buried organic material found within dune fields (e.g., charcoal, soils, bone, peat). For example, Sears (1961) and Watts and Wright (1966) reported some of the first ^{14}C ages from the Nebraska Sand Hills, which were obtained from organic material collected from drill cores. While these studies provided absolute ages from the Nebraska Sand Hills, Ahlbrandt et al. (1983) considered them to be unreliable as age indicators of dune activity, because they were sampled from inter-dune lake sediments, not directly from aeolian stratigraphy. The first study to provide ^{14}C ages in context with dune stratigraphy was that of David (1971), who used ^{14}C to date a series of buried soils through a small parabolic dune exposed in a road cut in the Brandon Sand

Hills of Manitoba. David (1971) concluded that paleosol development occurred on dune surfaces during times of mesic climate and that dune activity resumed when conditions were more arid. This investigation documented five periods of dune activity, shortly subsequent to ~3700, 2100, 1500, 900, and 400 years ago. David (1971) further argued that these periods of activity likely represented a near complete reactivation of the Brandon Sand Hills.

Within the next decade, several studies emerged using ^{14}C dating as the primary method of determining periods of prehistoric dune activity, and, as such, the number of studies which relied on ^{14}C dating increased dramatically. This was due largely to the development and availability of accelerator mass spectrometry (AMS) for ^{14}C dating in the late 1970s and early 1980s (Fig. 2.1). One important study published in this era was that of Ahlbrandt et al. (1983), in which they presented the first overview of dune field chronologies at that time from the Great Plains and the Rocky Mountain basins of Wyoming and Colorado. The authors also reported new ^{14}C ages of dune activity from the Nebraska Sand Hills. Moreover, this study was significant because it was the first to correlate dune activity in dune fields geographically distant from each other. Additionally, it was the first study to provide evidence for multiple Holocene dune activations across the Great Plains.

The next major advancement in Great Plains dune chronologies was the development and application of thermoluminescence (TL), infrared stimulated luminescence (IRSL), and optically stimulated luminescence (OSL) dating techniques. Thermoluminescence was first used as a technique to date dune activity in Rajasthan, India by Singhvi et al. (1982) and was subsequently applied to dunes in the Great Plains by Forman and Maat (1990). IRSL, originally developed by Hütt et al. (1988), was first applied in the Great Plains by Wolfe et al. (2001) to date dune activity in Saskatchewan. Finally, OSL, originally developed by Huntley et al. (1985), was initially used to date dune activity in the Ferris dunes of Wyoming (located outside the Great Plains; Stokes and Gaylord, 1993) and subsequently by Madole (1995) to date dune activity in Colorado. Luminescence dating, particularly OSL, was shown by these original studies to be extremely practical for recording periods of Great Plains dune activity because 1) the organic matter needed for ^{14}C dating is often limited in dune fields, 2) aeolian sedimentation is an ideal process for luminescence techniques in that it provides sand grains ample exposure to the sun, which resets the thermal or optical signal, and 3) OSL and other luminescence dating approaches generally date aeolian sedimentation (i.e., dune movement), whereas ^{14}C ages from these settings generally record the time at which organic matter accumulated in association with a relatively stable surface. As a consequence, luminescence ages are typically interpreted as dating intervals of dune activity, whereas ^{14}C ages from once stable surfaces only loosely bracket dune activity.

The rapid abandonment of ^{14}C-based chronologies and the widespread adoption of luminescence dating are evident in publication trends (Fig. 2.1). Optical dating (OSL and IRSL) is arguably the most significant advancement to appear in Great Plains dune studies, and, in many ways, it remains the best and usually the only way of developing dune chronologies. Optical dating has become widespread in the literature, and reviews of the technique have been published by Duller (2004), Lian and Roberts (2006), and Rhodes (2011). This is not to discredit the importance of ^{14}C dating in Great Plains dune studies; in fact, such ages from in situ charcoal, bone, and organic carbon from buried paleosols within dune stratigraphic sequences provide useful comparative age data to those derived from luminescence.

2.3. The North American Great Plains

The North American Great Plains is an expansive prairie (grassland) located in the geographic center of North America and is bound to the east by temperate forests, the north by boreal forests, the west by the Rocky Mountains, and the south by the Chihuahuan desert. Though many different Great Plains boundaries exist, this review has

Figure 2.2. Dune fields of the North American Great Plains (modified from Wolfe et al., 2009). The North American Great Plains is that defined by the United States Environmental Protection Agency Ecoregion Level 2 Map (USEPA, 2012).

adopted that of the United States Environmental Protection Agency Ecoregion Level 2 Map—an area of ~2.74 million km^2 (Fig. 2.2) (Table 2.1) (USEPA, 2012). Prior to

Table 2.1. Mapped dune field area of the Great Plains by state/province

State/Province	Great Plains Land Area (km²)[a]	Great Plains Dune Area (km²)[b]	Dunes % of Land Area
Canada			
Alberta	155,440	3040	1.96
Manitoba	72,342	1693	2.34
Saskatchewan	240,221	4496	1.87
Total	**468,003**	**9229**	**1.97**
United States			
Colorado	113,191	27,045	23.89
Iowa	136,579	–[c]	–
Kansas	212,592	16,352	7.69
Minnesota	77,819	530[d]	0.68
Missouri	70,204	–[c]	–
Montana	256,103	–[c]	–
Nebraska	200,001	70,818	35.41
New Mexico	103,635	15,252	14.71
North Dakota	182,884	9514	5.20
Oklahoma	142,184	15,881	11.17
South Dakota	199,516	3440	1.72
Texas	408,256	12,112	2.97
Wisconsin	1572	–[c]	–
Wyoming	73,535	3163	4.30
Total	**2,178,071**	**173,577**	**7.97**
Mexico			
Coahuila	29,378	–[c]	–
Nuevo León	38,932	–[c]	–
Tamaulipas	20,683	–[c]	–
Total	**88,993**	**–**	**–**
North American Great Plains			
Total	**2,735,067**	**182,806**	**6.68**

[a] Great Plains area was calculated in ArcGIS using the USEPA Ecoregion Level 2 Map boundary (USEPA, 2012) and WGS 1984 Datum.
[b] Dune area was calculated in ArcGIS using dune polygons modified from Wolfe et al. (2009) and Koop et al. (2012).
[c] States where no mapped dune fields are found within the boundaries of the Great Plains (isolated dunes may appear in county-level surficial geological maps).
[d] Dune area estimated from Grigal et al. (1976).

European colonization of the Great Plains, the region was dominated by short- and tall-grass communities, whereas today ~70% is used for agriculture including crop and rangeland (GCC, 2009). Natural vegetation presently consists of tall-grass prairie (e.g., Big Bluestem, *Andropogon geradi*; Indian Grass, *Sorghastrum nutans*; Switchgrass, *Panicum virgatum*) in the east, but then transitions to short-grass prairie (e.g., Blue Grama, *Bouteloua gracilis*; Buffalo Grass, *Buchloe dactyloides*) at ~100º west longitude. Areas in the far western Great Plains contain an abundance of sagebrush (*Artemisia spp.)* and yucca (*Yucca glauca*), whereas plant communities in the extreme southern Great Plains consist of a savannah-steppe vegetation (Kuchler, 1967).

The east-west transition in plant community composition is reflective of a strong meridional precipitation gradient. For example, mean annual precipitation decreases at a rate of ~100 mm for every 150 km between Denver, Colorado and Kansas City, Kansas (~900 km) (HPRCC, 2012). In addition to a pronounced east-west precipitation gradient, the Great Plains exhibits a strong seasonal north-south temperature gradient. During the summer (July), temperatures throughout the region remain relatively consistent averaging about 24º C; during the winter (January), however, temperatures in Saskatoon, Saskatchewan average -11.8º C, while those in San Antonio, Texas average 17.2º C. Average January and July temperatures and mean annual precipitation for major cities in the Great Plains are listed in Table 2.2.

Winds on the Great Plains are strong, variable, and reflective of seasonal shifts in mid-latitude cyclonic pressure systems influencing the region (Fargione et al., 2012). Schmeisser et al. (2010) synthesized the modern wind directions, drift potential, and resultant drift direction (see Fryberger, 1978; 1979) for the United States Great Plains, and their analysis concluded that the northern Great Plains (North Dakota, South Dakota) is dominated by northwesterly winds throughout much of the year, while the central Great Plains (Kansas, Nebraska) exhibit somewhat greater seasonal influence of northwesterly winds, which are dominant during the winter months, with southerly winds

Table 2.2. Temperature and precipitation data for major cities in the North American Great Plains

Location[a]	Lat. (°N)	Long. (°W)	Mean Jan. Temp (°C)	Mean July Temp (°C)	Mean Annual Precip. (mm)
Edmonton, AB	53.533	113.500	-11.7	17.5	476.9
Saskatoon, SK	52.133	106.683	-17.1	18.2	350.0
Winnipeg, MB	49.883	97.133	-17.8	19.5	513.7
Great Falls, MT	47.500	111.283	-6.0	20.1	373.9
Minneapolis, MN	44.983	93.266	-11.2	17.3	776.0
Casper, WY	42.833	106.317	-3.8	21.6	331.0
Omaha, NE	41.250	96.000	-6.4	24.7	778.5
Denver, CO	39.733	104.983	-0.1	23.3	394.2
Kansas City, MO	39.100	94.580	-3.5	25.8	977.6
Oklahoma City, OK	35.467	97.533	2.2	27.8	931.2
Albuquerque, NM	35.111	106.610	1.2	25.8	240.5
Dallas, TX	32.767	96.800	6.3	29.6	953.8
San Antonio, TX	29.417	98.500	9.6	29.4	819.0
Monterrey, N.L.	25.667	100.300	14.4	28.6	591.0

[a] Location of each cities can be referenced in Figure 2.2.

during the summer. Winds in the southern Great Plains (Texas) are still dominantly northerly, though southerly and southwesterly winds are present throughout the summer months. Seasonal and local variability in Great Plains winds can be observed in Table 2.3, which tabularizes January and July average wind vectors and velocities for major cities of the Great Plains.

Aeolian dunes are found throughout the Great Plains, and, although not all dune fields have been represented on published maps, it is likely that they can be found in all states and provinces of the Great Plains. As currently mapped (e.g., Muhs and Holliday, 1995; Muhs and Wolfe, 1999; Wolfe et al., 2009; Koop et al., 2012), dunes cover ~182,806 km^2, or ~6.68% of the Great Plains, ~39% of which are found in Nebraska (Table 2.1). Many dune fields are located in proximity to or within large alluvial river valleys, such as the Saskatchewan, North and South Platte, Arkansas, and Cimarron rivers (Fig. 2.2), and geochemical evidence has shown the sediment source of many Great

Table 2.3. Wind data for major cities in the North American Great Plains

Location[a]	Lat. (°N)	Long. (°W)	Jan. Mean Wind Vector (°)	Jan. Mean Wind Speed (m s^{-1})	July Mean Wind Vector (°)	July Mean Wind Speed (m s^{-1})
Edmonton, AB	53.533	113.500	180	3.1	270	3.4
Saskatoon, SK	52.133	106.683	270	4.2	270	4.1
Winnipeg, MB	49.883	97.133	180	4.8	180	4.1
Great Falls, MT	47.500	111.283	225	6.6	225	4.5
Minneapolis, MN	44.983	93.266	315	4.7	180	4.2
Casper, WY	42.833	106.317	225	7.6	225	4.7
Omaha, NE	41.250	96.000	337	4.9	360	3.9
Denver, CO	39.733	104.983	180	3.9	180	3.7
Kansas City, MO	39.100	94.580	203	4.9	180	4.1
Oklahoma City, OK	35.467	97.533	360	5.6	157	4.8
Albuquerque, NM	35.111	106.610	360	3.6	90	4.0
Dallas, TX	32.767	96.800	180	4.9	180	4.3
San Antonio, TX	29.417	98.500	360	3.9	157	4.1
Monterrey, N.L.	25.667	100.300	135 [b]	6.3 [b]	135 [b]	5.4 [b]

[a] Location of each cities can be referenced in Figure 2.2.
[b] Actual wind data is from Laredo, Texas, the nearest location with climatological records (~200 km north).
Climatological data obtained from Environment Canada National Climatic Data and Information Archive (ECNCD, 2012) and the National Oceanic and Atmospheric Administration (NOAA, 2012).

Plains dune fields to be these river systems (e.g., Muhs et al., 1996; Arbogast and Muhs, 2000; Muhs et al., 2000; Muhs and Holliday, 2001; Muhs, 2004). Aeolian sand of the Great Bend Sand Prairie of Kansas has, for example, been linked to the Arkansas River (Arbogast and Muhs, 2000) and the Casper dunes of Wyoming to the North Platte River (Muhs, 2004). Certain dune fields may be linked to alluvial systems despite being some distance from their source, such as the Wray dunes of Colorado and the South Platte River (Fig. 2.2) (Muhs et al., 1996). Other dune fields, such as the Nebraska Sand Hills (Fig. 2.2), likely formed from a variety of sources including reworked, early-Quaternary alluvial and aeolian sands, outcropping Tertiary sandstones, and even some input from alluvial rivers (Winspear and Pye, 1996; Muhs, 2004). Still other dune fields were derived from sandy glacial outwash or deflated glacial lake deposits, which became available for reworking by the wind as the Laurentide Ice Sheet retreated during the latest Pleistocene and early Holocene (Muhs and Wolfe, 1999; Wolfe et al., 2004).

Dune morphology varies by dune field, and most individual dune fields display diverse and complex morphologies. These present-day, complex morphologies may be the result of prehistoric wind shifts (e.g., Sridhar et al., 2006; Schmeisser et al., 2010), multiple Holocene activations, which have reworked older dune generations, and modern human disturbance. Parabolic or dome morphologies (Fig. 2.3A–C, E) can be found in most Great Plains dune fields, however, many variations of these morphologies are observed, such as the hairpin parabolic dunes of the Casper dunes (Fig. 2.3C). Those dune forms more common to arid environments can be found throughout the Great Plains, though their distribution is mostly limited to larger dune fields (i.e., > 4000 km^2). These arid-environment morphologies consist of barchan, barchanoid ridges (Fig. 2.3D, G), and transverse dunes (Fig. 2.3F). In most locations where characteristic arid dune morphologies are found, such as the Nebraska Sand Hills and the Arkansas River dunes, they are overprinted by more recent episodes of smaller parabolic or dome dune development (Smith, 1965; Ahlbrandt and Fryberger, 1980; Forman et al., 2008). Lunette-type dunes are common throughout the Great Plains as well, especially in Texas (Fig. 2.3H) (Holliday, 1997) and Kansas (Bowen and Johnson, 2011).

Due to the morphological complexities of individual dune fields and limitations of discussing them in this chapter, latitude and longitude coordinates for all dune fields discussed herein are provided in Appendix II. This file should be used to further explore the complex dune morphologies of dune fields throughout the Great Plains using a virtual globe program like Google Earth.

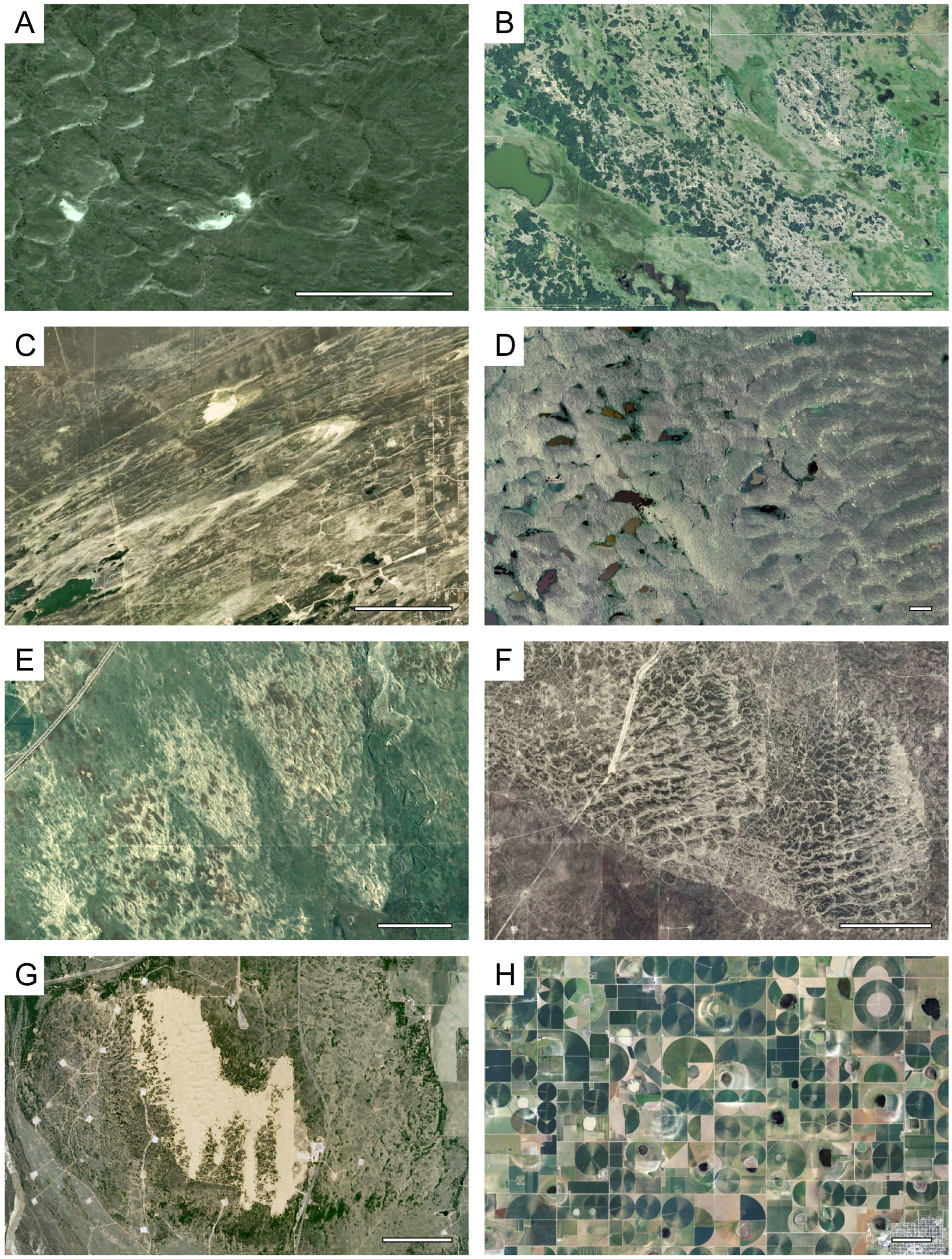


Figure 2.3. Representative aerial views of common dune morphologies found in dune fields of the Great Plains. North is up, and a 1km scale bar is located in the bottom-right of all images. A) mostly stabilized parabolic dunes of the Great Sand Hills, Saskatchewan; B) remnant parabolic dunes in the Minot dunes, North Dakota; C) hair-pin parabolic dunes in the Casper dunes, Wyoming; D) parabolic dunes atop barchanoid ridges in the Nebraska Sand Hills, Nebraska; E) mostly active parabolic dunes in the Fort Morgan dune field, Colorado; F) parabolic dunes and transverse ridges in the Arkansas River dunes, Kansas; G) active barchanoid ridges in the Little Sahara State Park, Cimarron River dunes, Oklahoma; H) playas and associated lunettes east of Lubbock, Texas on the Southern High Plains. Canadian imagery was extracted from the Saskatchewan Geospatial Imagery Collaborative (www.flysask.ca), and U.S. Imagery from the United State Geological Survey National Map Viewer (www.nationalmap.gov).

2.4. Regional record of dune activity

To facilitate discussion of individual dune field chronologies, the North American Great Plains has been divided into four geographical regions: the 1) Canadian (Alberta, Manitoba, Saskatchewan); 2) northern (Minnesota, North Dakota, South Dakota, Wyoming); 3) central (Colorado, Kansas, Nebraska); and 4) southern Great Plains (New Mexico, Oklahoma, Texas). Within each region, the prehistory of dune activity is discussed beginning with the oldest documented activity. Dune field locations, activation chronologies, and sub-regional paleodrought records are displayed in Figures 2.4–2.7. Tabular summaries of all dune studies by region appear in Tables 2.4–2.7, and individual ages, which comprise the chronologies from each region, are found in Appendix I.

2.4.1. Canadian Great Plains

More than 130 discrete dune fields, collectively covering ~10,000 km^2, are found in the Canadian Great Plains of provinces Alberta, Manitoba, and Saskatchewan (Fig. 2.4) (Wolfe et al., 2004). The relatively small size of Canadian dune fields, compared to those of the central Great Plains, is due in part to their isolated sandy glacial outwash sediment sources, which were deposited during retreat of the Laurentide Ice Sheet (Wolfe et al., 2000). Muhs and Wolfe (1999) speculated that, due to these isolated sources, many of the dune fields in the Canadian Great Plains have not migrated far from their sediment source. The relationship between dune activity in the Canadian Great Plains and the Laurentide Ice Sheet is evident also in dune field chronologies, i.e., the earliest (oldest) activity occurred in dune fields that were ice-distal (Wolfe et al., 2000; Wolfe et al., 2004; Wolfe et al. 2007b). A list of named dune fields and related studies appear in Table 2.4.

The oldest dune activity in the Canadian Great Plains is that documented in the late Pleistocene and early Holocene, following retreat of the Laurentide Ice Sheet. In Alberta, this activity was initiated between ~16,000 and ~14,000 years ago and later in Saskatchewan prior to 9,000 years ago (Wolfe et al., 2004). Dune activity at this time

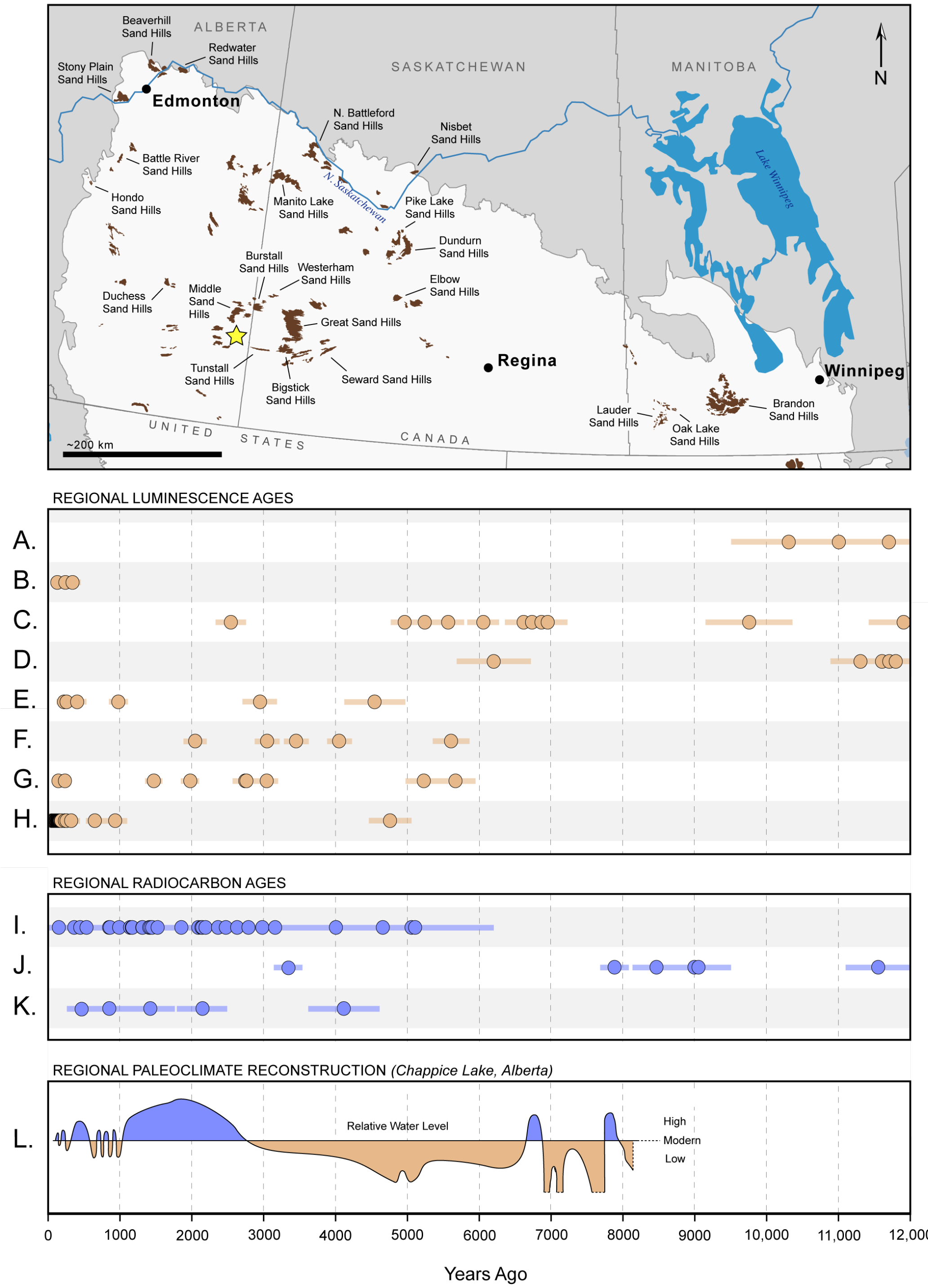


Figure 2.4. Dune chronologies of the Canadian Great Plains and a representative proxy record of Holocene paleoclimate. Age data error bars reflect that reported by original authors—typically 1 to 2σ. A) High Level dunes, Wolfe et al., 2007b; B) Elbow Sand Hills, Wolfe et al., 2007a; C) various dune fields in Saskatchewan (see Table 2.4), Wolfe et al., 2006; D) various dune fields in Alberta (see Table 2.4), Wolfe et al., 2004; E) Duchess Sand Hills, Wolfe et al., 2002b; F) Brandon Sand Hills, Wolfe et al., 2002a; G) Elbow and Dundurn Sand Hills, Lian et al., 2002; H) various dune fields in Saskatchewan (see Table 2.4), Wolfe et al., 2001; I) Brandon Sand Hills, Wolfe et al., 2000; J) Dundurn Sand Hills, Turchenek et al., 1974; L) Brandon Sand Hills, David, 1971; K) Holocene fluctuation in the water level of Chappice Lake, Alberta (star on map), Vance et al., 1992.

Table 2.4. Dune fields and chronological studies of the Canadian Great Plains

Dune Field	Studies	^{14}C Ages[b]	Lum. Ages[c]
Alberta			
Battle River Sand Hills	Wolfe et al. 2004	–	3
Bear River Sand Hills[a]	Wolfe et al. 2004	–	2
Beaverhill Sand Hills	Wolfe et al. 2004	–	1
Chisholm Sand Hills[a]	Wolfe et al. 2004	–	1
Decrene Sand Hills[a]	Wolfe et al. 2004	–	1
Duchess Sand Hills	Wolfe et al. 2002b	–	6
Economy Creek Sand Hills[a]	Wolfe et al. 2004	–	1
Edson Sand Hills[a]	Wolfe et al. 2004	–	1
Fort Assiniboine Sand Hills[a]	Wolfe et al. 2004	–	1
Grovedale Sand Hills[a]	Wolfe et al. 2004	–	1
High Level dunes[a]	Wolfe et al. 2007b	–	4
Holmes Crossing Sand Hills[a]	Wolfe et al. 2004	–	1
Hondo Sand Hills	Wolfe et al. 2004	–	1
Lac La Biche Sand Hills[a]	Wolfe et al. 2004	–	1
Lodgepole Sand Hills[a]	Wolfe et al. 2004	–	1
Nelson Lake Sand Hills[a]	Wolfe et al. 2004	–	1
Pipestone Sand Hills[a]	Wolfe et al. 2004	–	1
Redwater Sand Hills	Wolfe et al. 2004	–	1
Rocky Mt. House Sand Hills[a]	Wolfe et al. 2004	–	1
Stony Plain Sand Hills	Wolfe et al. 2004	–	3
Watino Sand Hills[a]	Wolfe et al. 2004	–	1
Windfall Sand Hills[a]	Wolfe et al. 2004	–	1
Manitoba			
Brandon Sand Hills	David 1971	5	–
Brandon Sand Hills	Wolfe et al. 2000	32	–
Brandon Sand Hills	Wolfe et al. 2002a	–	5
Saskatchewan			
Bigstick Sand Hills	Wolfe et al. 2001	–	5
Burstall Sand Hills	Wolfe et al. 2001	–	5
Dundurn Sand Hills	Lian et al. 2002	–	2
Dundurn Sand Hills	Turchenek et al. 1974	6	–
Elbow Sand Hills	Lian et al. 2002	–	7
Elbow Sand Hills	Wolfe et al. 2007a	–	3

Saskatchewan continued.			
Fort a la Corne Sand Hills[a]	Wolfe et al. 2006	–	3
Gowen Site	Wolfe et al. 2002a[d]	1	–
Grandora	Wolfe et al. 2002a[d]	1	–
Great Sand Hills	Wolfe et al. 2001	–	7
Manito Lake Sand Hills	Wolfe et al. 2006	–	4
Moon Lake	Wolfe et al. 2002a[d]	1	–
Nisbet Sand Hills	Wolfe et al. 2006	–	2
North Battleford Sand Hills	Wolfe et al. 2006	–	2
Pike Lake	Wolfe et al. 2002a[d]	5	–
Qu' Appelle Valley	Wolfe et al. 2002a[d]	1	–
Seward Sand Hills	Wolfe et al. 2001	–	14
Tunstall Sand Hills	Wolfe et al. 2001	–	1
Westernham Sand Hills	Wolfe et al. 2001	–	2
	Total	**52**	**97**

[a] Dune field is in close proximity to the Great Plains but not found within the USEPA Ecoregion Level 2 Map boundary (USEPA, 2012).
[b] Includes conventional, $\delta^{13}C$ corrected, and AMS ^{14}C ages.
[c] Includes optical luminescence (IRSL, OSL) and thermoluminescence (TL).
[d] Archaeological and geological ^{14}C ages previously reported by Morlan et. al (2001).

reflects deflation of sandy glacial outwash, which eventually ceased as the boreal forest expanded and winds weakened and shifted to a dominantly northwesterly vector. These environmental changes occurred transgressively between ~13,000 and ~9,000 years ago from southwestern Alberta to northeastern Saskatchewan (Wolfe et al., 2004) (Fig. 2.4). Wolfe et al. (2007b) investigated the High Level dune field in northern Alberta (Fig. 2.4), which, since its last recorded activity ~14,000 and 10,000 years ago, has been stabilized by boreal forest vegetation. Morphology and chronology of the High Level dune field appear to reflect the same change in winds documented by Wolfe et al. (2004). Other dune fields at the margin of the Canadian Great Plains/boreal forest boundary of Saskatchewan, including the Manito Lake, Nisbet, North Battleford, and Fort a la Corne Sand Hills, were active ~11,000 years ago (Wolfe et al., 2006) (Fig. 2.4). The Elbow and Dundurn Sand Hills of central Saskatchewan were also active ~11,300 years ago and remained so for several millennia (Lian et al., 2002) (Fig. 2.4). Wolfe et al. (2002c) speculated that aeolian activity in the Elbow and Dundurn Sand Hills reflected the beginning of a regional shift in climate towards increased aridity during the middle Holocene.

Records of middle-Holocene dune activity in the Canadian Great Plains are limited compared to those of the latest Pleistocene and earliest Holocene. The early study of Turchenek et al. (1974) documented paleosol development in the Dundurn Sand Hills ~8000 ^{14}C years BP, and they argued that aeolian sediments below these paleosols reflected early-Holocene dune activity, whereas subsequent aeolian sediments overlying the paleosols were deposited when the dune field reactivated in response to increased aridity after ~8000 ^{14}C years BP. Lian et al. (2002), using luminescence dating, later documented aeolian activity in the Dundurn Sand Hills during the middle Holocene ~7500–5000 years ago, which Wolfe et al. (2002c) attributed to warming associated with the middle-Holocene Warm Period (a.k.a., Holocene Climate Optimum, Altithermal). At the time of their study, Wolfe et al. (2002c) concluded that the middle-Holocene record of dune activity in the Canadian Great Plains was of sufficient magnitude to completely rework most dune sediments, thereby effectively erasing any evidence of early Holocene activity. Subsequent studies by Wolfe et al. (2004) and Wolfe et al. (2006), however, provided significant evidence for this early-Holocene activity. Limited dune activity in the Brandon Sand Hills of Manitoba (Fig. 2.4) was also reported by Wolfe et al. (2002a) prior to ~5200 years ago, which correlates well to that documented by the Saskatchewan studies of Lian et al. (2002) and Wolfe et al. (2002c).

The most robust chronologies of prehistoric dune activity for the Canadian Great Plains (i.e., those supported with the greatest number of ages) are those indicating dune activity during the late Holocene. For example, dune activity was reported prior to ~2300, ~2000–1400, ~1000–600 years ago, and after ~500 years ago in the Brandon Sand Hills (Wolfe et al., 2000, 2002a). These episodes of dune activity were believed to reflect prehistoric droughts, purportedly more intense than those documented from historical records. Prehistoric climate changes associated with the Medieval Climatic Anomaly (MCA) were also reported to have forced dune activation in the Elbow and Dundurn Sand Hills after ~1400 years ago (Lian et al., 2002; Wolfe et al., 2002c).

A significant record of late-Holocene dune activity exists for the Great Sand Hills of Saskatchewan (Fig. 2.4), with the latest episode of dune activity, beginning ~200 years ago and lasting up until only ~100 years (Wolfe et al., 2001). Although ages from their chronology reflect dune activity in the 1800s, Wolfe et al. (2001) argued that their ages better represent dune re-stabilization following dune activity, which likely occurred in the 1700s as a result of decreased precipitation. Their conclusions were supported with regional precipitation proxy data, which indicate drought during the 1700s and mesic conditions in the 1800s (e.g., Case and MacDonald, 1995; Sauchyn and Beaudoin, 1998). In the Duchess Sand Hills of southeastern Alberta (Fig. 2.4), dune activity occurred ~4500–2000 and ~400–200 years ago, and dune stability between ~1000 and ~400 years ago (Wolfe et al., 2002b). Dune activity in the Duchess dune field correlates well with periods of regional aridity, and dune stability correlates well with periods of increased moisture (Fig. 2.4). Wolfe et al. (2002b) attributed a lack of dune field activity during the last 200 years in the Duchess dune field to a prevalence of wind from the northwest, which has transported greater moisture to the area. Conversely, the Great Sand Hills of Saskatchewan, which were active within the last 200 years, were dominated by a greater component of drier northerly and southerly winds (Wolfe et al. 2001).

In an effort to investigate whether recent dune activity was the result of changes in climate or other causes, Wolfe et al. (2007a) examined linkages between aboriginal occupation and dune activity in the Elbow Sand Hills of Saskatchewan. Their study concluded that currently stabilized dunes were active prior to European occupation, which suggested that the aboriginal cultures' use of sand dunes for herding and impounding bison may have led to dune activation until the appearance of European agriculture, which served to stabilize the landscape. Wolfe et al. (2007a) further cautioned that care should be taken when interpreting dune activity solely as a response to changes in climate, and that other non-climatic factors, such as aboriginal disturbances, may be responsible for dune field activation. In a similar study, Wolfe and Hugenholtz (2009), though providing no new ages of dune activity, used light detection and ranging (LIDAR) imagery to illustrate that currently stabilized parabolic dunes in the Great Sand Hills had formed from active barchan dunes about 200 years ago. Based on comparisons to proximal tree-ring series from Manitoba, Saskatchewan, and Alberta (e.g., Luckman and Wilson, 2005; St. George et al., 2009), Wolfe and Hugenholtz (2009) concluded that barchan dunes in the Great Sand Hills formed under cool and dry climates when local water tables were lower, and that the transformation to stabilized parabolic dunes occurred under warmer and more humid conditions. Wolfe and Hugenholtz (2009) further concluded that large changes in dune field morphology can reflect short-term response to climate, and that these types of responses in dune fields may overprint those of longer-duration shifts in climate.

Several periods of increased aridity reflected in Canadian dune field chronologies are recorded in other paleoclimatic records as well, though the number of records that extend beyond the Holocene is limited. Vance et al. (1992) used mineralogy and plant macrofossils to reconstruct an 8,000-year drought record from Chappice Lake, Alberta (Fig. 2.4). Their record indicated multiple periods of sustained drought, particularly during the middle Holocene. Additionally, they documented multiple episodes of shorter duration droughts between 1000 and 600 years ago, which reflected drought following the MCA. These droughts were subsequently followed by increased moisture between 600 and 100 years ago, which correlates well to the LIA and dune stability in many Canadian Great Plains dune fields. Historic droughts of the 1930s and 1950s were also recorded within their record.

2.4.2. Northern U.S. Great Plains

The northern Great Plains of the United States encompasses the states of North Dakota, Minnesota, Montana, South Dakota, and Wyoming (Fig. 2.5). Dune fields in this region are significantly smaller than those of the central Great Plains and have received relatively little attention. Nevertheless, several robust chronologies of dune activity spanning most of the Holocene have been derived from dune fields in the northern Great Plains (Table 2.5).

The earliest record of dune activity in northern Great Plains is that documented in the Casper dunes of Wyoming (Fig. 2.5). Radiocarbon ages of 9830 ± 350 ^{14}C years BP and 10,060 ± 170 ^{14}C years BP were derived from charcoal and a bison bone, respectively, found in a parabolic dune within the Casper dunes of Wyoming, suggesting the dune field formed during the early Holocene (Albanese, 1974). Decades later, Halfen et al. (2010) provided an expanded chronology of dune activity from the Casper dunes. Utilizing a combination of OSL and AMS ^{14}C dating, they documented the initial formation of the Casper dunes during the early to middle Holocene, between ~10,000–6200 years ago. The Killpecker dunes of the Great Divide Basin of Wyoming also record early-Holocene dune activity (Mayer & Mahan, 2004).

Many dune fields in the northern Great Plains, particularly those of North Dakota, owe their existence to glacial lakes associated with the retreat of Laurentide Ice Sheet around the Pleistocene-Holocene transition, and, therefore, they do not record evidence of dune activity until at least the middle Holocene. For example, the Minot dunes (Fig. 2.5) were constructed from deflated sandy sediments of Glacial Lake Souris, which drained ~11,000 years ago (Teller, 1987; Lord, 1988), but no ages from the Minot dunes support dune activity immediately following its drainage. In a similar setting, the dunes of the Sheyenne Delta (Fig. 2.5), a subaqueous fan deposit of a major tributary to Glacial Lake Agassiz, mobilized following the draining of the lake, though the dune sediment itself likely originated from the Sheyenne River, not lacustrine sands (Running,

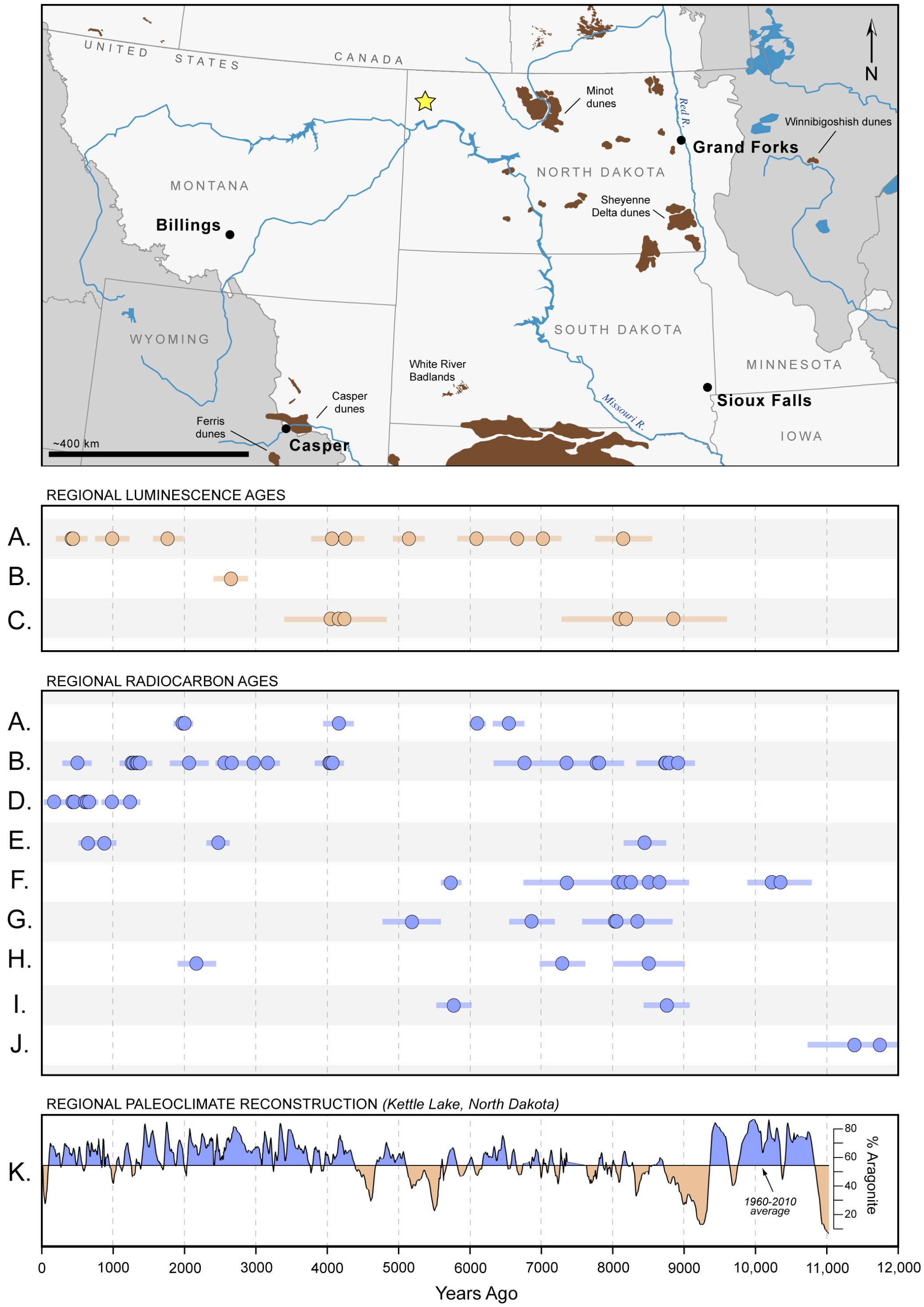


Figure 2.5. Dune chronologies of the northern U.S. Great Plains (and adjacent areas) and a representative proxy record of Holocene paleoclimate. Age data error bars reflect that reported by original authors—typically 1 to 2σ. A) Casper dunes, Halfen et al., 2010; B) White River Badlands dunes, Rawling et al., 2003; C) Ferris dunes, Stokes and Gaylord, 1993; D) Minot dunes, Muhs et al., 1997a; E) Sheyenne Delta dunes, Running, 1996; F) Sheyenne Delta dunes, Running, 1995; G) Ferris dunes, Gaylord, 1990; H) Ferris dunes, Gaylord, 1982; I) Winnibigoshish dunes, Grigal et al., 1976; J) Casper dunes, Albanese, 1974; K) Holocene record of percent aragonite from Kettle Lake, North Dakota (star on map), Grimm et al., 2011.

Table 2.5. Dune fields and chronological studies of the northern U.S. Great Plains

Dune Field	Studies	^{14}C Ages[b]	Lum. Ages[c]
Minnesota			
Winnibigoshish dunes[a]	Grigal et al. 1976	2	–
North Dakota			
Minot dunes	Muhs et al. 1997a	8	–
Sheyenne Delta dunes	Running 1995	9	–
Sheyenne Delta dunes	Running 1996	4	–
South Dakota			
White River Badlands dunes	Rawling et al. 2003	25	1
Wyoming			
Casper dunes	Albanese 1974	2	–
Casper dunes	Halfen et al. 2010	6	12
Ferris dunes[a]	Gaylord 1982	3	–
Ferris dunes[a]	Gaylord 1990	6	–
Ferris dunes[a]	Stokes and Gaylord 1993	–	6
	Total	**65**	**19**

[a] Dune field is in close proximity to the Great Plains but not found within the USEPA Ecoregion Level 2 Map boundary (USEPA, 2012).
[b] Includes conventional, $\delta^{13}C$ corrected, and AMS ^{14}C ages.
[c] Includes optical luminescence (IRSL, OSL) and thermoluminescence (TL).

1995; 1996). Initial dune activity in the Sheyenne Delta dunes was documented after ~8000 years ago, which is consistent with ages on the final drainage of Glacial Lake Agassiz (e.g., Barber et al., 1999; Roy et al., 2011).

Middle-Holocene dune activity was recorded in other smaller, isolated dune fields of the northern Great Plains, such as dune and aeolian cliff-top deposits in the White River Badlands of South Dakota after ~8000 and ~6000 years ago (Rawling et al., 2003) (Fig. 2.5). Dune fields in Wyoming, including the Casper and Ferris dunes (Fig. 2.5) record dune activity ~8,000 years ago (Stokes and Gaylord, 1993; Halfen et al., 2010). Limited evidence from the Winnibigoshish dunes in Minnesota suggest that they activated between ~8000–5000 years ago in response to increased temperatures and extreme drought (Grigal et al., 1976). Though the Winnibigoshish dunes are some distance east of the current Great Plains boundary, at the time of their formation, they were located on the boundary of the Great Plains, which likely extended 100 km further east in Minnesota than at present (Dean, 1997).

Dune activity ~4000 years ago is fairly commonplace in dune fields of the northern Great Plains. Major dune fields in Wyoming record activity at this time: the Ferris dunes were active after ~4300 years ago (Stokes and Gaylord, 1993); the Casper dunes were active after ~4100 years ago (Halfen et al., 2010); and the Seminole dunes were active between ~5000 and 500 years ago (Miller, 1986). Aeolian cliff-top deposits were deposited in the White River Badlands after ~3700 years ago (Rawling et al., 2003), and dune activity reinitiated in the Sheyenne Delta dunes ~3700 years ago (Running 1995; 1996).

As with chronologies from the Canadian Great Plains, the most complete records of dune activity for the northern Great Plains are those of the late Holocene. Aeolian cliff-top deposits were deposited in the White River Badlands after ~2500 and ~1300 years ago (Rawling et al., 2003). Running (1995; 1996) documented dune field activity in the Sheyenne Delta dunes prior to 2400 years ago and between ~900 and 600 years ago. Running (1995; 1996) proposed that periods of aeolian activity in the Sheyenne Delta dunes at this time were the result of droughts similar in magnitude and duration to those of historical droughts (i.e., 1930s, 1950s). The Minot dunes were active prior to and following brief periods of stability at ~1000 and ~500–600 years ago (Muhs et al., 1997a). Muhs et al. (1997a) attributed past Holocene activity in the Minot dunes as being caused most likely by severe droughts accompanied by warm temperatures, an interpretation they based on historical observations of activity in Minot dunes during the 1930's Dust Bowl.

Several non-dune paleoclimatic records exist for the northern Great Plains, in part, due to the abundance of kettle and pothole lakes associated with the retreat of the Laurentide Ice Sheet. Recently, Grimm et al. (2011) provided a 13,000-year record of climate and vegetation change from Kettle Lake, North Dakota (Fig. 2.5). Their record indicated that the early Holocene was generally wet, with the middle Holocene having greater precipitation variability including several multi-decadal droughts, some of which correlate well with documented dune activity in the region. The late Holocene was also characterized with decade-scale precipitation variability, though, in general, it was wetter than the middle Holocene. Additionally, MCA droughts are reflected in this record and correlate well with ages of northern Great Plains dune activity.

2.4.3. Central U.S. Great Plains

The central Great Plains, defined as the states of Colorado, Nebraska, and Kansas, contain the greatest concentration of dune fields, which in total accounts for 63% of all mapped dune field area in the entire Great Plains (Table 2.1; Fig. 2.6). While much of this dune area encompasses the Nebraska Sand Hills, the largest dune field in North America, dune fields of Colorado and Kansas are similarly extensive and include the Wray dunes (~7000 km^2) and Great Bend Sand Prairie (~4000 km^2), respectively (Fig. 2.6). Considering the size and abundance of dune fields in the central Great Plains, it is no surprise that this area contains the highest number of individual dune activation chronologies, which are derived from over 60% of all ^{14}C and luminescence ages currently comprising the entire Great Plains activation data set (Table 2.5).

Earliest sand activity in the central Great Plains is documented during the latest Pleistocene beginning ~22,500 years ago in the Fort Morgan dunes of Colorado in the form of sand sheet and dune deposits (Forman et al., 1995; Madole, 1995) (Fig. 2.6). Though activity in Colorado at this time is supported only by a handful of numerical ages, loess deposition, which may be the fine-grained component of these dune fields, is well documented in the area (Aleinikoff et al., 1999; Muhs et al., 1999). Muhs et al. (1999) linked loess deposition in Colorado at this time to the collapse of the Pinedale glaciers in the Rocky Mountains, which was derived from glaciogenic silts transported in

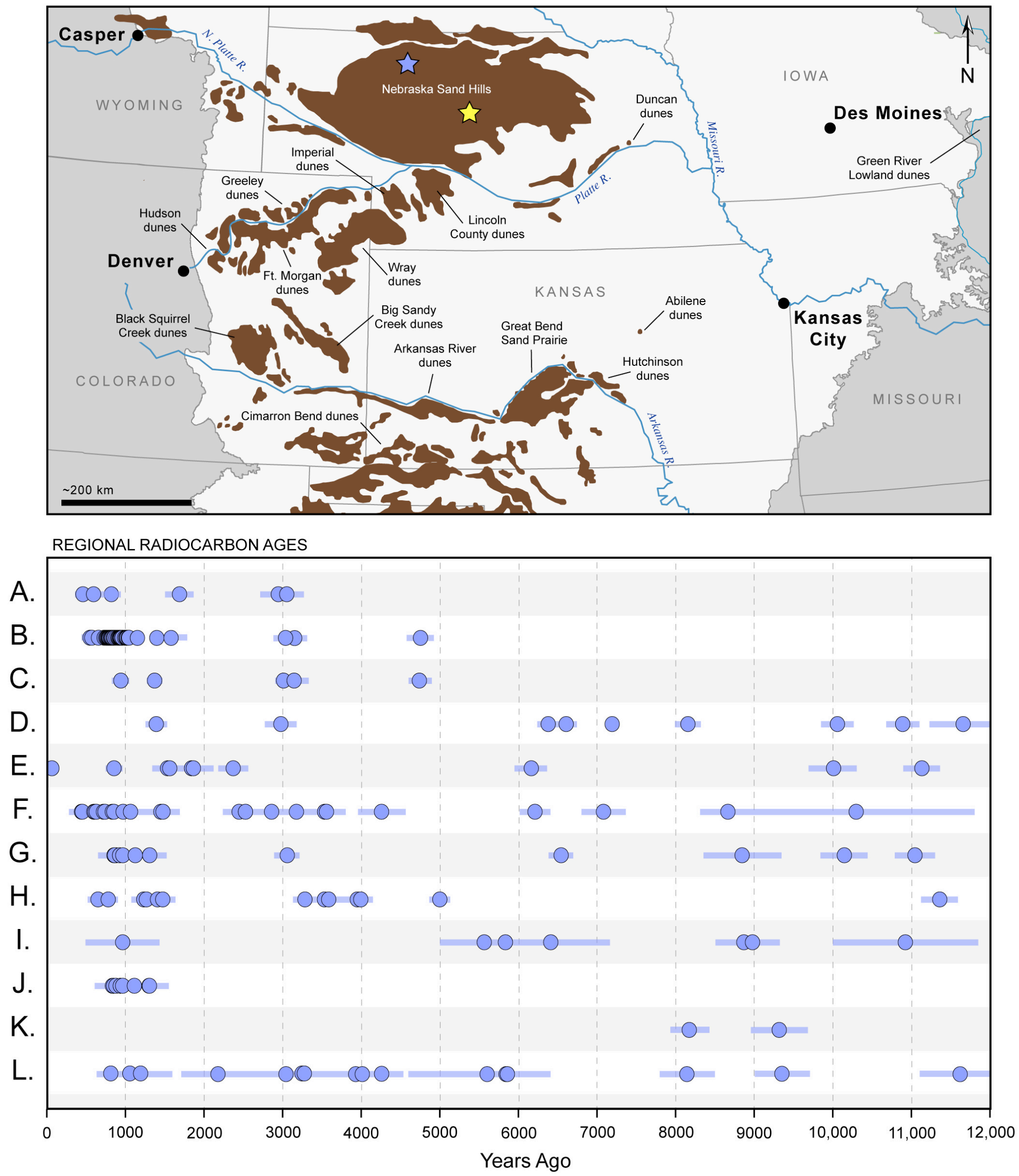


Figure 2.6. Dune chronologies of the central U.S. Great Plains and representative proxy records of Holocene paleoclimate. Age data error bars reflect that reported by original authors—typically 1 to 2σ. A) Green River Lowlands, Miao et al., 2010; B) Nebraska Sand Hills, Mason et al., 2004; C) Nebraska Sand Hills, Goble et al., 2004; D) Cimarron Bend dunes, Olsen and Porter, 2002; E) Nebraska Sand Hills, Stokes and Swinehart, 1997; F) Great Bend Sand Prairie, Arbogast, 1998; G) Fort Morgan dunes, Madole, 1995; H) Nebraska Sand Hills, Loope et al., 1995; I) Fort Morgan dunes and neighboring dune fields, Forman et al., 1995 (study includes ages from Forman et al., 1992); J) Fort Morgan dunes, Madole, 1994; K) Hudson dunes, Forman and Maat, 1990; L) North Park dunes and Nebraska Sand Hills, Ahlbrandt et al., 1993. M) Hutchinson dunes, Halfen et al., 2012; N) Cimarron Bend Dunes, Werner et al., 2011; O) Nebraska Sand Hills activity record and inter dune lake paleoclimatic record (yellow star on map), Schmieder et al., 2011; P) Nebraska Sand Hills, Mason et al., 2011; Q) Abilene dune, Hanson et al., 2010; R) Duncan dunes, Hanson et al., 2009; S) Arkansas River dunes, Forman et al., 2008; T) Nebraska Sand Hill dune and the regional loess record, Miao et al., 2007a; U) Nebraska Sand Hills and Wray dunes, Forman et al., 2005; V) Fort Morgan dunes, Clarke and Rendell, 2003; W) Magnitude of Holocene aeolian activity interpreted from sediment cores extract Jumbo Valley, Nebraska Sand Hills (blue star on map), Nicholson and Swinehart, 2005.

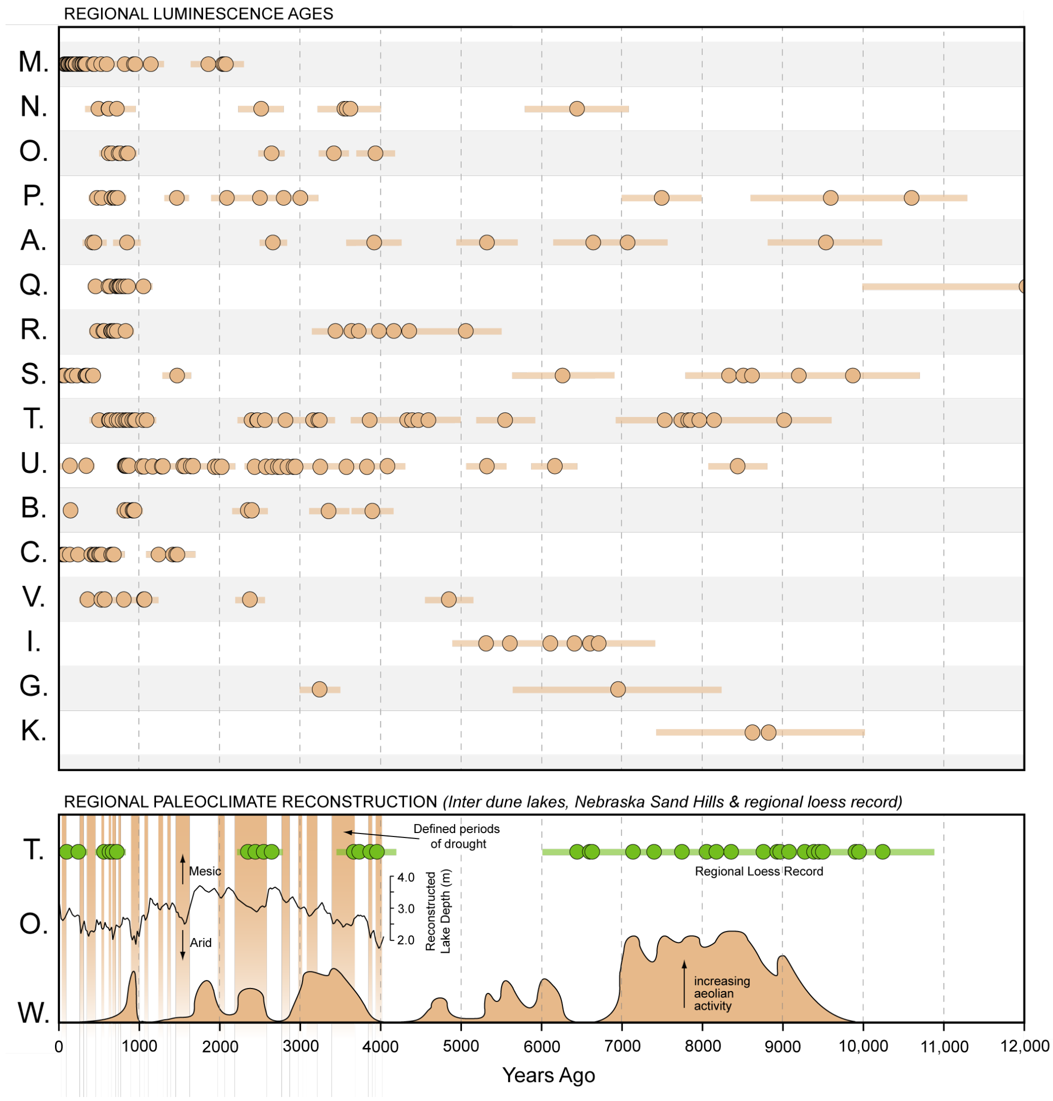


Figure 2.6 Continued. See figure caption on the previous page.

Table 2.6. Dune fields and chronological studies of the central U.S. Great Plains

Dune Field	Studies	^{14}C Ages[b]	Lum. Ages[c]
Colorado			
Fort Morgan dunes	Forman et al. 1992	4	–
Fort Morgan dunes	Madole 1994	8	–
Fort Morgan dunes	Forman et al. 1995	4	8
Fort Morgan dunes	Madole 1995	13	2
Fort Morgan dunes	Clarke & Rendell 2003	–	8
Greeley dunes	Forman et al. 1992	1	–
Hudson dunes	Forman & Maat 1990	2	2
North Park dunes	Ahlbrandt et al. 1983	4	–
Illinois			
Green River Lowlands dunes[a]	Miao et al. 2010	6	17
Kansas			
Abilene dunes	Hanson et al. 2010	–	17
Arkansas River dunes	Forman et al. 2008	–	22
Cimarron Bend dunes	Olson & Porter 2002	9	–
Cimarron Bend dunes	Werner et al. 2011	–	8
Great Bend Sand Prairie	Arbogast 1996	27	–
Hutchinson dunes	Halfen et al. 2012	–	60
Nebraska			
Duncan dunes	Hanson et al. 2009	–	17
Nebraska Sand Hills	Ahlbrandt et al. 1983	12	–
Nebraska Sand Hills	Loope et al. 1995	14	–
Nebraska Sand Hills	Stokes & Swinehart 1997	10	8
Nebraska Sand Hills	Goble et al. 2004	5	37
Nebraska Sand Hills	Mason et al. 2004	59	10
Nebraska Sand Hills	Forman et al. 2005	–	29
Nebraska Sand Hills	Miao et al. 2007[d]	–	44
Nebraska Sand Hills	Mason et al. 2011	–	37
Nebraska Sand Hills	Schmieder et al. 2011	–	9
Wray dunes	Forman et al. 2005	–	4
	Total	**178**	**339**

[a] Dune field is in close proximity to the Great Plains but not found within the USEPA Ecoregion Level 2 Map boundary (USEPA, 2012).
[b] Includes conventional, $\delta^{13}C$ corrected, and AMS ^{14}C ages.
[c] Includes optical luminescence (IRSL, OSL) and thermoluminescence (TL)
[d] Count does not include ages previously reported in Goble et al. (2004) and Mason et al. (2004).

14,000 years ago. Mason et al. (2011) concluded that their reported ages probably represented only a terminal stage of dune formation, and that, in all likelihood, larger dunes forms in the Nebraska Sand Hills were active much earlier. They concluded that substantial dune activity ~17,000–14,000 years ago reflected a regional climate that was colder and drier with shorter growing seasons than that responsible for dune field activity during the Holocene. Goble et al. (2004) recorded limited dune activity in the Nebraska Sand Hills ~15,000–9200 years ago, which supports the chronology provided by Mason et al. (2011). While outside the boundary of the Great Plains, Pleistocene dune activity was also documented in the Green River Lowlands of Illinois ~17,500 years ago (Miao et al., 2010) (Fig. 2.6). Miao et al. (2010) concluded that dune activity likely initiated after sandy glacial outwash was deflated following the catastrophic drainage of Glacial Lake Scuppernong, which drained through the Green River valley, Illinois.

Early-Holocene dune activity is documented in most major dune fields of the central Great Plains, including the Nebraska Sand Hills ~9600–6500 years ago (Miao et al. 2007a), and prior to ~8000 and ~9200 years ago (Ahlbrandt et al. 1983; Goble et al. 2004). Dune activity was recorded in the Hudson, Greeley and Fort Morgan dunes of Colorado (Fig. 2.6) during the early Holocene between ~9000 and 7000 years ago (Forman and Maat, 1990), ~9500–5500 years ago (Forman et al., 1992), and prior to ~9000 years ago (Madole, 1995). Forman et al. (2008) documented episodic aeolian activity in the Arkansas River dunes of Kansas (Fig. 2.6.) between ~9800 and ~6300 years ago as well.

Middle-Holocene dune activity in the Nebraska Sand Hills has been reported by several authors, including Loope et al. (1995), who documented dune activity prior to ~4300 years ago based on basal ^{14}C ages obtained from inter-dune lakes within the Nebraska Sand Hills. Stokes and Swinehart (1997) reported dune activity ~5700 years ago and attributed that activity to decreases in moisture sufficient to reactivate large barchan dunes of the Nebraska Sand Hills. Optical ages from the Nebraska Sand Hills, provided by Goble et al. (2004), indicated dune activity ~4000 years ago and possibly earlier episodes ~6100, ~5700, and ~5300 years ago, however, these later periods of activity were not recognized beyond more than one locality. Lastly, Miao et al. (2007a) documented dune activity during the middle Holocene, but their composite record, which included age data from Goble et al. (2004) and Mason et al. (2004), suggested aeolian activity increased ~4500 years ago and continued into the late Holocene. Downstream from the Nebraska Sand Hills, adjacent to the Platte River, are the Duncan dunes (Fig. 2.6), which were also active ~4400–3400 years ago (Hanson et al. 2009).

Many dune fields in Colorado and Kansas were active during the middle Holocene. Forman and Maat (1990) and Forman et al. (1992) documented dune activity in the Hudson and Greeley dunes after ~5500 and ~4800 years ago. Additional periods of activity were recorded in the neighboring Fort Morgan dunes between ~8000 and ~1000 years ago, though the activity following ~8000 years ago likely reflected multiple episodes of dune activity, not a single event (Madole, 1995). Forman et al. (1995) used a combination of ^{14}C and TL ages to confirm multiple dune activations in the Fort Morgan dunes during the middle Holocene ~6000 and ~4500 years ago. Forman et al. (1995) concluded that dune activity in Colorado during the middle Holocene may have been linked to a shift in the Bermuda High, which allowed for a greater influence of continental air masses in eastern Colorado. Clarke and Rendell (2003) reported dune activity in the Fort Morgan dunes ~4900 years ago, which could have resulted as sediment flux increased from the South Platte River during times of sustained drought. Farther east in Kansas, Forman et al. (2008) reported evidence for episodic aeolian activity between ~9800 and ~6300 years ago in the Arkansas River dunes.

Evidence of late-Holocene dune activity in the central Great Plains is extensive, and, in some cases, complete reactivation of dune fields during the late Holocene has overprinted chronological evidence of older activity (e.g., Hutchinson dunes; Halfen et al., 2012). The first study to provide a ^{14}C-based chronology of dune activity from the

Nebraska Sand Hills documented most activity between ~3000 and ~1500 years ago (Ahlbrandt et al., 1983). Loope et al. (1995) documented reworked aeolian sand in dune-damed lakes within the Nebraska Sand Hills within the last ~1500 years. Muhs et al. (1997b), using AMS ^{14}C dating, recorded dune activity at multiple sites in the Nebraska Sand Hills, and, based on the stratigraphy of dated paleosols and aeolian sediments, suggested the Nebraska Sand Hills had reactivated at least twice in the past ~3000 years ago, with one period of activity within the past 800 years. This activity in the last 800 years, they argued, was caused by droughts of greater intensity than those responsible for the 1930's Dust Bowl. Muhs et al. (1997b) provided a mineralogical assessment of aeolian sand in the Nebraska Sand Hills, which indicated that, despite young ages of dune activity, sediment from the Nebraska Sand Hills has had a long aeolian history, perhaps spanning back prior to the last glacial cycle.

Luminescence-based chronologies support earlier ^{14}C-based chronologies, which suggested that the Nebraska Sand Hills reactivated several times during the late Holocene. Specifically, Stokes and Swinehart (1997) documented dune activity between ~4000 and ~2000 years ago and within the last 800 years, and reasoned that frequent, 20-year-duration or longer droughts probably caused repeated dune activity during the late Holocene. Goble et al. (2004), employing a combination of ^{14}C and OSL, reported late-Holocene activity in the Nebraska Sand Hills ~4000, ~3600, ~2300, ~800, ~400, and ~200 years ago, which correlate to those periods identified by Stokes and Swinehart (1997). Mason et al. (2004) dated dune activity from inter-dune sand sheet deposits in the Nebraska Sand Hills. The youngest of these sand sheets was found to have been deposited between ~1000 and ~700 years ago, which compares well with ages of dune activity documented by Goble et al. (2004). Given that inter-dune sand sheet accumulation could not have occurred unless the local water table had dropped, it was concluded that this aeolian activity ~1000–700 years ago was initiated by drought.

Forman et al. (2005) documented six periods of late-Holocene dune activity in the Nebraska Sand Hills, centered on ~1400, ~700, ~500, ~240, ~140, and ~70 years ago. Young, near-surface sediments found at all study sites were assumed to represent dune activity within the last 100 years, probably reflecting activity during the 1930's Dust Bowl. The authors recognized regional correlations in MCA dune activity between their study and several other dune fields ~1000–800 years ago, and further argued that dune activity ~500 years ago may be linked to documented 16th century North American megadroughts. Miao et al. (2007a), recognizing widespread correlation of dune activity within the Nebraska Sand Hills and throughout the much of the Great Plains ~1000–700 years ago, suggested that dune activity at this time was the result of sustained megadroughts associated with the MCA. Although not exclusively a dune activation study, that by Schmieder et al. (2011) reported several OSL ages of dune activity in the Nebraska Sand Hills between ~900 and ~700 years ago, which correlates well with activity documented in many previous studies. Dune activity was recorded downstream of the Nebraska Sand Hills in the Duncan dune field of eastern Nebraska ~800–500 years ago, which correlates well with activity in the Nebraska Sand Hills following the MCA, suggesting that megadroughts during this time covered large spatial expanses of the Great Plains (Hanson et al. 2009).

Dune fields of Colorado record evidence of significant aeolian activity during the late Holocene, but the majority of available ages are reported from only the Fort Morgan dunes. For example, Forman et al. (1992) documented dune activity in the Fort Morgan dunes between ~4800 and ~1000 years ago, and within the last 1000 years. Madole (1994; 1995) also recorded episodic aeolian sand mobilization during the past 1000 years within the Greeley and Fort Morgan dunes. Forman et al. (1995) supported earlier chronologies from the Fort Morgan dunes with TL ages that indicated dune activity during the past ~1000 years. Most recently, IRSL ages from the Fort Morgan dunes reported by Clarke and Rendell (2003) indicated discrete periods of aeolian activity ~2400, ~1100, ~800, ~600–500, and ~370 years ago.

Late-Holocene dune activity is widespread in all studied dune fields of Kansas. Using ^{14}C ages extracted from buried soils, Arbogast (1996) and Arbogast and Johnson (1998) constructed a sequence of periodic landscape stability in the Great Bend Sand Prairie of central Kansas ~2300, ~1400, ~1100, ~900, ~700 and ~500–300 years ago, all of which were followed by dune sedimentation. Arbogast (1996) concluded that the numerous late-Holocene episodes of dune activity reflected the likelihood of the Great Bend Sand Prairie mobilizing under even modest future drought conditions. Arbogast and Johnson (1998) further concluded that, based on the $\delta^{13}C$ values from the ^{14}C age samples, dune activity in the area occurred during relatively warm periods and that future dune activation is inevitable given possible future climate scenarios for the region.

Forman et al. (2008) reported evidence for episodic aeolian activity centered ~1500, ~400, ~180, and ~70 years ago in the Arkansas River dunes, all of which correlate well with tree-ring, reconstructed drought records (Cook and Krusic, 2004). Hanson et al. (2010) documented dune activity in the Abilene dunes of north-central Kansas (Fig. 2.6) between ~1100 and ~500 years ago. Based on the correlation among dune activity in the Abilene dunes and other Great Plains dune fields ~1000 years ago, Hanson et al. (2010) concluded that this activity could be related to major climatic changes associated with the MCA, which resulted in spatially extensive megadroughts. Recently, Halfen et al. (2012) presented a dune activation chronology for the Hutchinson dunes (Fig. 2.6), which spanned the last 2200 years and reported three significant periods of dune field activity: ~2100–1800, ~1000–800, and ~600–70 years ago. Halfen et al. (2012) again concluded that dune activity ~1000–800 year ago was associated with the MCA. Furthermore, they argued that dune activity within the past 600 years correlates well with peak cold intervals of the LIA, and that, if LIA droughts were present in the Great Plains, they were more localized and geographically limited to areas of the southern and western Great

Plains (i.e., south and west of Nebraska), in contrast to those of the MCA which covered most of the Great Plains.

Unlike the northern Great Plains, non-dune paleoclimatic records that span several millennia are lacking in the central Great Plains. Two records that do span the entire Holocene are the regional loess record (e.g., Mason, 2001; Mason et al., 2003; Miao et al., 2007a, 2007b; Muhs et al., 2008) and a speleothem record from Iowa (e.g., Denniston et al., 1999). The regional loess record, which was synthesized by Miao et al. (2007a), indicates that major dune activity during the middle and late Holocene is roughly coeval with regional loess deposition (Fig. 2.6). Beyond the regional loess records, very few paleoclimatic records exist that extend back over 2000 years. One such record, however, comes from a series of cores collected within inter-dune lakes in the Nebraska Sand Hills and provides good evidence for alternating wet and dry periods for the last 4000 years (Schmieder et al., 2011). This record documents greater intensity droughts (i.e., decade to centennial scale) between ~4000 and 2000 years ago, whereas those droughts recorded during the last 2000 years were more variable and shorter in duration. Several droughts identified by Schmieder et al. (2011) correlate to periods of dune activity in the central Great Plains, in particular those which occurred ~4000–3000, ~2400, and after ~1000 years ago.

2.4.4. Southern U.S. Great Plains

New Mexico, Oklahoma, and Texas exhibit a high concentration of dune fields and sand sheets, collectively covering over 43,000 km^2 (Fig 7; Table 2.1), though they remain relatively understudied, especially compared to dune fields of the central Great Plains (Table 2.7). Beyond the importance of dune activity to the climatic history of the region, archaeological and geoarchaeological studies have demonstrated the affinity of early Americans (e.g., Paleoindians) to dune fields (e.g., the Clovis Site; Holliday, 2001).

The earliest record of dune activity in the southern Great Plains was reported from isolated transverse lunettes, which are associated with hundreds of playas covering the panhandle of Texas (Fig. 2.7). Numerous AMS ^{14}C ages place initial lunette formation on the Southern High Plains between ~25,000–15,000 years ago (Holliday, 1997). Holliday et al. (2008) dated aeolian sand deposits within the basins of some playas on the Southern High Plains of Texas between ~14,000–10,000 years ago. Holliday (1997) recorded middle-Holocene reactivation in lunettes ~8000–5000 years ago, and Holliday et al. (2008) dated aeolian deposition in playas between ~8600–4700 years ago.

Dune fields and sand sheets in Oklahoma record middle-Holocene dune activity, though the number of ages from Oklahoma supporting this activity is very limited and only reported from a single dune field. Cordova et al. (2005) bracketed the accumulation of aeolian sand between two paleosols with AMS ^{14}C ages of ~6500 and ~3000 years ago at an isolated site within the Cimarron River valley dunes (Fig. 2.7).

While middle-Holocene ages of dune activity are largely absent from dune fields in Oklahoma, late-Holocene activity is widely documented, yet still not to the extent of the central Great Plains. Lepper and Scott (2005) reported dune activity ~3300 years ago and between ~900– 700 years ago in close proximity to those sites analyzed by Cordova et al. (2005), which themselves contained evidence of dune activity at ~200 years ago. Werner et al. (2011) also provided a chronology of dune activity from Cimarron Bend dunes in southwestern Kansas and the Panhandle region of Oklahoma (Figs. 6–7) which documented aeolian activity ~3800 years ago and between ~1000 and 400 years ago. These ages of dune activity were consistent with those from many other dune fields throughout the central and southern Great Plains. Of note, however, was the conclusion that older dunes generally have a greater abundance of pedogenic fine particles and are less likely to reactivate under modest shifts in decreased precipitation due to the ability of these particles to maintain cohesion even with limited moisture. Younger dunes, conversely, may not contain these fine particles, which renders them more susceptible to

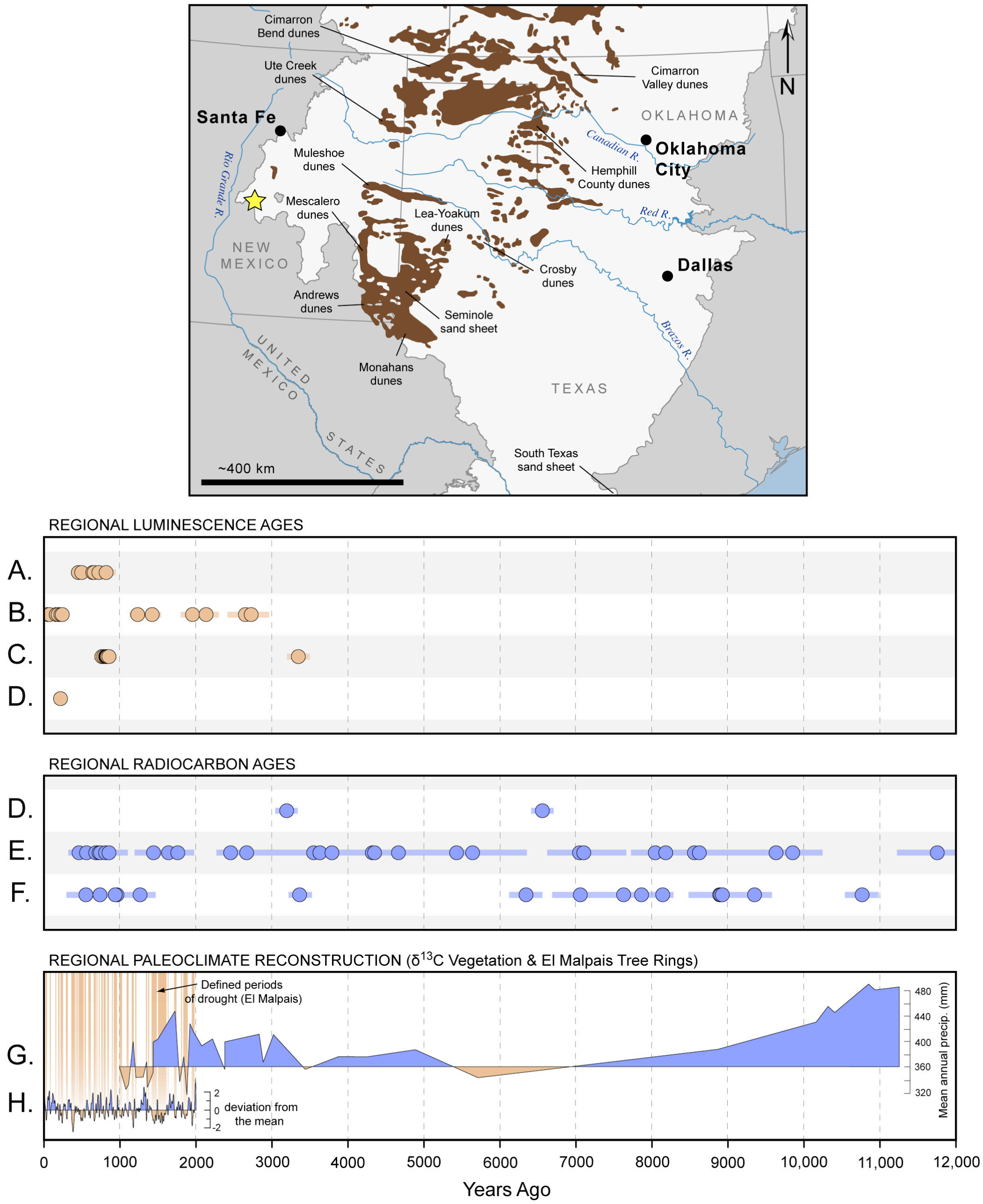


Figure 2.7. Dune chronologies of the southern U.S. Great Plains and a representative proxy record of Holocene paleoclimate. Age data error bars reflect that reported by original authors—typically 1 to 2σ. A) Cimarron Bend dunes, Werner et al., 2011; B) South Texas sand sheet, Forman et al., 2009; C) Cimarron Valley dunes, Lepper and Scott, 2005; D) Cimarron Valley dunes, Cordova et al., 2005; E) High Plains lunettes, Holliday 1997; F) various dune fields in the Southern High Plains (see Table 2.7), Holliday 2001; G) mean annual precipitation based on $\delta^{13}C$ ratio, Abo Arroyo, New Mexico (yellow star on map), Hall and Penner, 2012; H) tree-ring reconstructions from El Malpais National Monument, New Mexico, Grissino-Mayer, 1996.

Table 2.7. Dune fields and chronological studies of the southern U.S. Great Plains

Dune Field	Studies	^{14}C Ages[b]	Lum. Ages[c]
New Mexico			
Muleshoe dunes	Holliday 2001	8	–
Lea-Yoakum dunes	Holliday 2001	3	–
Southern High Plains Lunettes	Holliday 1997	8	–
Other isolated dunes	Holliday 2001	1	–
Oklahoma			
Cimarron Bend dunes	Werner et al. 2011	–	6
Cimarron River Valley dunes	Cordova et al. 2005	2	1
Cimarron River Valley dunes	Lepper & Scott 2005	–	12
Texas			
Andrew dunes	Holliday 2001	1	–
Lea-Yoakum dunes	Holliday 2001	1	–
Muleshoe dunes	Holliday 2001	8	–
Other isolated dunes	Holliday 2001	6	–
South Texas sand sheet[a]	Forman et al. 2009	–	12
Southern High Plains Lunettes	Holliday 1997	25	–
	Total	**59**	**31**

[a] Dune field is in close proximity to the Great Plains but not found within the USEPA Ecoregion Level 2 Map boundary (USEPA, 2012).
[b] Includes conventional, $\delta^{13}C$ corrected, and AMS ^{14}C ages.
[c] Includes optical luminescence (IRSL, OSL) and thermoluminescence (TL)

activation. Werner (2011) concluded that this non-linear relationship between drought and dune activity, may result in some dune fields of the Great Plains activating under specific climate conditions whereas others remain stable, and that this relationship may account for dune field chronologies that display widely different activation ages even though they are in geographic proximity. The authors acknowledge that it is “still appropriate to link past periods of dune activity to drought,” nonetheless, caution is warranted when making drought-dune activation linkages solely based on age data alone (Werner et al., 2011, p. 275).

Late-Holocene dune activity is widely documented in major dune fields of Texas and New Mexico including the Muleshoe, Lea-Yoakum, and Andrews dunes (Fig. 2.7) (Holliday, 2001). Dune activity in the Muleshoe dunes was reported after ~1300, ~700, ~500 years ago, in the Lea-Yoakum dunes following ~3400 years ago, in the Andrews dunes after ~2300 years ago, and aeolian sand deposition was reported in the Seminole sand sheet between ~400 and ~300 years ago. Moreover, all dune fields studied by Holliday (2001) appeared to have been active within the last 200 years.

Non-dune paleoclimatic records that span the Holocene are very scarce in the southern Great Plains; though some are available from the far western boundary of the Great Plains and alpine regions in New Mexico. Hall and Penner (2012) used $\delta^{13}C$ values from radiocarbon ages to produce a ~13,000-year record of temperature, precipitation, and vegetation change in the southern Great Plains (Fig. 2.7). The record indicates a cooler and wetter period at the end of the Pleistocene followed by conditions similar to today between 11,000 and 9,000 years ago. Though the $\delta^{13}C$ for the middle Holocene is incomplete, Hall and Penner (2012) speculate that the middle Holocene was warmer and drier than today. The middle Holocene was followed by greater precipitation and slightly cooler temperatures ~3300–1400 years ago. Lastly, warm and dry conditions returned to the southern Great Plains during after 1400 years ago, though the authors acknowledge a gap in data during the past 1000 years. Though the record provided by Hall and Penner contains some gaps in data, it does provide a reliable record of long term climate in the southern Great Plains, and at least one of these gaps (~1000 years ago to present) can be filled with additional paleoclimatic records. For example, Grissino-Mayer et al. (1997), produced a 2200-year record of drought from tree rings at El Malpais, New Mexico. Though this record only extends 2200 years and ~300 km from the Great Plains, it does document several extreme droughts, notably ~1500, ~1200–900 and ~500–400 years ago—the latter two of these periods correlate well with documented dune activity in the southern Great Plains.

2.4.5. Summary of dune field chronologies

Dune fields of the North American Great Plains were first active during the latest Pleistocene or early Holocene, although significant variability in timing occurs among dune fields. Holliday (2001), for example, documented dune activity in the Southern High Plains as early as ~25,000 years ago, whereas Mason et al. (2011) and Forman et al. (2008) reported the earliest episode of dune activity about ~17,000–16,000 years ago in the Nebraska Sand Hills and Arkansas River dunes, respectively. Mason et al. (2011) acknowledged, however, that the Nebraska Sand Hills were probably somewhat older, a conclusion that was supported by other authors (e.g., Smith, 1965; Winspear and Pye, 1996; Muhs et al., 1997b). In Canada, timing of initial dune field activity between ~16,000 and ~14,000 years ago has been linked to the retreating Laurentide Ice Sheet (e.g., Wolfe et al., 2004; Wolfe et al., 2007b). Elsewhere in the Great Plains, initial dune field activation may be related to major morphology changes in the Great Plains fluvial systems responsible for producing dune field sediment (e.g., Muhs et al., 1996; Muhs, 2004; Forman et al., 2008). Finally, some dune fields were formed from deflated sediment following the drainage of glacial lakes, though this activity did not occur until the middle Holocene (e.g., Running 1995, 1996; Muhs et al., 1997a).

Middle-Holocene dune field activity is well documented in many Great Plains dune fields, especially those of the central Great Plains. For example, dune field activity was documented in the Nebraska Sand Hills between ~9600–6500 years ago (Miao et al., 2007a); dune fields in Colorado ~8000 (Madole, 1994; 1995), ~6000 (Forman et al., 2005), and ~4900 years ago (Clarke and Rendell, 2003); and ~9800–6300 years ago in the Arkansas River dunes (Forman et al., 2008). Despite this rich record of middle-Holocene activity, many chronologies from dune fields in other areas of the Great Plains have little evidence to support dune activity in the middle Holocene, such as the Minot dunes (Muhs et al., 1997a), Great Bend Sand Prairie (Arbogast, 1996); multiple dune fields of Canada (Wolfe et al., 2001; 2004), dune fields of Oklahoma (Cordova et al., 2005; Lepper and Scott, 2005; Werner et al., 2011), and the Hutchinson dunes (Halfen et al., 2012).

Nearly all Great Plains dune fields were active in the late Holocene, with several chronologies reporting multiple reactivations within the past 2000 years (e.g., Holliday, 2001; Forman et al., 2005; Forman et al., 2008; Halfen et al., 2012). Another important aspect of dune field chronologies that record late-Holocene activity is the apparent region-wide occurrence of synchronous dune activity associated with the MCA, between ~1100 and ~700 years ago. This activity is documented in Canada (e.g., Wolfe et al., 2000; 2001; 2002b; Lian et al., 2002), the northern Great Plains (e.g., Running, 1995; 1996), Nebraska Sand Hills (e.g., Goble et al., 2004; Mason et al., 2004; Forman et al., 2005; Miao et al., 2007a), dune fields of Colorado (e.g., Forman et al., 1992; Madole, 1994; Clarke and Rendell, 2003), eastern Great Plains dune fields (e.g., Hanson et al., 2009; 2010; Halfen et al., 2012) and those dune field in the Southern High Plains (e.g., Holiday 2001; Werner et al., 2011). Medieval Climatic Anomaly drought has been documented in other Great Plains paleoclimatic records, such as those from lake cores, tree-ring series, and alluvial stratigraphy (e.g., Laird et al., 1996; 1998; Woodhouse and Overpeck, 1998; Daniels and Knox, 2005; Cook et al., 2007; 2009). Several of the most recent OSL chronologies have also successfully documented dune field activity during the 1930s. Records from the Nebraska Sand Hills (Forman et al., 2001) and dune fields in Kansas (Forman et al., 2008; Halfen et al., 2012), for example, are corroborated by historical documents describing the widespread dune activity in the Great Plains during the 1930‘s Dust Bowl. The well-documented region-wide activation of dune fields during the late Holocene additionally underscores the importance of using dune activity as a proxy for drought by documenting significant destabilization of these aeolian systems. If Great Plains dune fields were only relict features of climate change associated with the deglaciation of North America and Pleistocene-Holocene transition, then late-Holocene dune activity should not be recorded in the stratigraphic record of almost every dune field studied in the Great Plains. Moreover, the fact that most Great Plains dune fields have reactivated several times throughout the late Holocene suggests a high probability that they will activate in the future given that the Great Plains climate over the past 3000 years is more reflective of today, than of the Pleistocene or early Holocene (Muhs et al., 1997a; Miao et al., 2010).

The vast majority of chronologies in this review contend that their reported dune activity was initiated by decreased moisture, and these researchers support their records by correlating them to other Great Plains drought proxy records (e.g., Fritz et al., 1991; Dean et al., 1996; Grissino-Mayer, 1996; Laird et al., 1996; Woodhouse and Overpeck, 1998; Fritz et al., 2000; Stahle et al., 2000; 2007; Schmieder et al., 2011). The limitation of using these proxies, however, is that they are at times restricted in spatial coverage and in some instances, such as in lake sediments, are of coarser resolution (Woodhouse and Overpeck, 1998; Fritz, 2008). In fact, only a limited number of Great Plains paleoclimatic records, other than dune field and loess stratigraphies, extend beyond the last 2000 years, and even fewer span the entire Holocene. Of those studies that encompass the Holocene (e.g., Dean et al., 1996; Dennison et al., 1999; Grimm et al., 2011; Hobbs et al., 2011; Hall and Penner, 2012), multiple droughts are recognized, including severe droughts during the middle Holocene and multiple long-duration (>20 years) droughts within the last 2000 years, though significant variability exists in the exact timing and magnitudes of the drought recorded in each record.

Despite the general consensus that Great Plains dune activity is caused by drought, some recent studies have emphasized the complexity of individual dune fields and cautioned that other factors, such as localized destabilization events, may undermine the regional signal of climate (Wolfe et al., 2007a; Wolfe and Hugenholtz, 2009; Halfen, 2010; Hanson, 2010; Werner et al., 2011; Halfen et al., 2012). Examples of localized factors that have been documented to contribute to dune field activity include: pre-European disturbance of dune fields by early americans, fire, and bison; feedback from other pedologic and geomorphic processes; and rapid influxes of sediment, or lack there of, which could be related directly or indirectly to changes in climate as well.

2.5. Dune field chronology limitations and considerations

2.5.1. Spatial and temporal limitations

The sheer number of dune activation data points (i.e., individual ages of dune field activity) for the North American Great Plains should make possible the analyses of spatial and temporal patterns of past dune activity and, by extension, patterns of past climatic events. The principle limitation of these chronologies, at least on a regional scale, is, however, that they contain large spatial and temporal gaps in data. For example, most of the 800 ages comprising chronologies of Great Plains dune activity are not distributed proportionately throughout the Great Plains. Furthermore, these chronologies lack consistent sampling schemes and more often than not record long-term stratigraphic hiatuses rather than detailed histories of dune activity. Specific reasons for gaps in current chronologies are the result of both faulty research design and the natural complexity of dune fields. Research design-related gaps in spatial and temporal data are created through a variety of ways, but primarily through unintentional biases in selecting dune fields for study and partialities in sampling dunes within a specific dune field.

An unintentional bias in selecting dune fields for study is evident in the widely imbalanced number of dune activation ages comprising current chronologies. For example, the Nebraska Sand Hills is arguably the most studied dune field on the Great Plains (e.g., Mason et al., 2011 and references therein), and expectedly so because of its size, complex geomorphic and chronologic history, and paleoclimatic importance. Nevertheless, the nine chronologies extracted from the Nebraska Sand Hills, comprised of 274 individual ages, are at least perceived to have a greater regional importance than chronologies developed from smaller dune fields. In comparison to the Nebraska Sand Hills, the Arkansas River, Minot, and Wray dunes, though lesser in size, are still large and relevant dune fields, yet their chronological database is limited to only 32 ages. Several authors have argued that individual dune fields have complex geomorphic histories or that dune fields may have lagged responses to climate change (e.g., Miao et al., 2007a; Wolfe and Hugenholtz, 2009; Werner et al., 2011; Halfen et al., 2012). Based on these factors alone, it may not be appropriate to link dune activity in Texas, Oklahoma, Kansas, or even Colorado to dune activity in the Nebraska Sand Hills. Even a modestly expanded chronology from larger dune fields such the Arkansas River and Wray dune field may serve as a better comparison to those dune fields not located in close proximity to the Nebraska Sand Hills.

An additional factor limiting current chronologies are the gaps in temporal data, which reflect, in part, the tendency of chronologies to only record young episodes of dune activity. This can be seen in early studies of the Nebraska Sand Hills, which until recently had not yet produced the chronological data to support wide-spread dune activity during the Pleistocene, even though geomorphic and geochemical evidence has long suggested it (Smith, 1965; Ahlbrandt et al., 1983; Loope et al., 1995; Winspear and Pye, 1996; Muhs et al., 1997b). The reasons for this limitation again may be due to limitations in time and resources, which may preclude a thorough sampling. On the other hand, this limitation may also be completely unrelated to the investigators' approach, but rather caused by the complexities in dune field geomorphology and the limitations in our ability to derive chronological data from geomorphically complex dune fields. For example, the sedimentation process of a typical dune includes 1) deflation of sediment on the lee side of a dune, 2) saltation of sand downwind to the brink, and 3) sliding of sand down the slipface of a dune (e.g., Pye and Tsoar, 1990; Tsoar and Blumberg, 2002). In this idealized process, individual dune forms might recycle their sediment as they migrate. Understanding this process is particularly important to chronology development, especially those based solely on OSL ages (the modern chronologic standard in the Great Plains), because later episodes of dune activity may completely erase earlier aeolian sedimentation events, i.e., earlier records of dune activity. Researchers can adjust their sampling strategy such that they sample parabolic dune wings versus dune crests in an attempt to collect an older sample; however, in the case of complex parabolic dune patterns, which are found in many Great Plains dune fields, it may be impossible to differentiate the geomorphology of specific parabolics (McKee, 1979; Bailey and Bristow, 2004).

In other cases still, recent dune activity may have been so intense that a complete reworking of dune forms occurs. For example, the Hutchinson dunes of Kansas contains a record of dune activity, which based on chronology and stratigraphy, began ~2,000 years ago (Halfen et al., 2012). Despite stratigraphic information available from the dune field and an abundant chronology that supports an initial dune field formation ~2,000 years ago, the geomorphology of the parabolic dunes comprising the dune field suggest an older age. Specifically, the Hutchinson dunes lie north of their sediment source, but their morphology indicates they formed under northerly winds. Halfen et al. (2012) concluded that the Hutchinson dunes must have first activated prior to the activity recorded in their stratigraphy, and that subsequent dune activity in the last 2,000 years was significant enough to completely re-organize the dune field, essentially erasing evidence of the older dune activity. Similar chronological hiatuses are common in arid dune systems throughout the globe (Singhvi and Porat, 2008).

In an ideal case, which can be found in many Great Plains dune fields, multiple episodes of dune activity are separated by buried paleosols. These paleosols result from prolonged stability brought about by increased moisture and vegetation growth, which acts to anchor a dune field (Muhs and Maat, 1993; Muhs and Holliday, 1995; Wolfe, 1997). An example of a well-developed regional paleosol is the Haplargid soil (informal term derived from soil taxonomic classification) found in Wyoming dune fields. The Haplargid soil formed between ~4500 and 2000 years ago and effectively separates middle- and late-Holocene dune activity in Wyoming (e.g., Albanese 1974; Albanese and

Frison, 1995; Eckerle, 1997; Halfen et al., 2010). Significant well distributed paleosols have been reported in other dune fields as well, for example, the Nebraska Sand Hills contain paleosols that have been correlated over large geographic areas (e.g., Goble et al., 2004; Mason et al., 2004). Other widely recognized paleosols are found in the Fort Morgan dunes of Colorado (Madole, 1995), and Dundurn Sand Hills of Saskatchewan (Turchenek et al., 1974; Lian et al., 2002; Wolfe et al., 2002c). Many dune fields, however, do not contain paleosols but only have isolated paleosol development found in individual dune forms, such as the Arkansas River dunes (Forman et al., 2008), the Duncan dunes (Hanson et al., 2009), Abilene dunes (Hanson et al., 2010), and Hutchinson dunes (Halfen et al., 2012). Further exploration of Great Plains dune fields may yield more regionally synchronous paleosols, like those of the regional loess record (e.g., Muhs et al., 1999; Mason et al., 2003; Miao et al., 2007b; Muhs et al., 2008), but given the absence of this stratigraphy in dune fields thus far, it is unlikely that dune fields will ever have a regionally recognized stratigraphy comparable to loess deposits.

2.5.2. Age data considerations

Beyond the primary limitation of gaps in spatial and temporal data, there are ancillary considerations to contemplate when attempting correlation of regional dune activity. One of these considerations is that early dune activation chronologies produced from ^{14}C ages are not comparable to the more recent OSL-based chronologies, in that radiocarbon ages only bracket dune activity, whereas OSL provides an age of the actually sedimentation event. While ^{14}C chronologies can be calibrated for comparison with modern OSL chronologies, errors are still inevitable given advancements in dating techniques. These advancements have played a major role in terms of determining reliable ages and in constraining errors associated with the ages. For example, the transition from conventional ^{14}C ages to AMS ^{14}C ages significantly improved age precision (Beukens, 1992; Törnqvist, 1992), and, because less material is needed for

AMS ^{14}C dating, the potential for contamination of samples from younger and older material is usually reduced, leading to more accurate ages (Beukens, 1992). Calibrating ^{14}C ages for comparison with optical ages does not necessarily provide a true representative calendar age given that uncertainties exist in the calibration curves themselves (e.g., Stuiver and Remier 1993; Fairbanks et al., 2005). These uncertainties are small and typically associated with error calibrations; nevertheless, age accuracy and precision will always remain a concern when comparing calibrated ^{14}C ages to luminescence ages.

Similarly, advancements in luminescence dating have led to new procedures for determining equivalent doses (D_e) (e.g., multiple aliquot additive dose or single aliquot regeneration; SAR), which ultimately resulted in more accurate ages (Duller 2004; Lian and Roberts, 2006). Furthermore, refined D_e protocols have resulted in reduced errors: whereas early IRSL and TL ages had large errors of 10 % to 20% (e.g. Forman and Maat, 1990; Stokes and Gaylord, 1993; Forman et al., 1995), ages produced using SAR (e.g. Hanson et al., 2009; Halfen et al., 2010; Hanson et al., 2010; Werner et al., 2011) have smaller errors, on the order of 5 to 10%. A final issue encountered when comparing age data from older studies to those of newer studies, whether ^{14}C or luminescence based, is that the age datum has changed, e.g., ^{14}C dating uses the datum of 1950 (Taylor, 1987, p. 97), whereas luminescence studies use a datum that typically corresponds to the year of analysis, though not all studies report an age datum.

Overall, the practical temporal resolution currently possible using luminescence and ^{14}C to determine periods of dune activity on the Great Plains are centennial-scale, and at best, decadal in some cases. As such, the potential errors of older chronologies associated with calibration or older D_e protocols, should not significantly alter major conclusions when comparing to new chronologies to older ones. It is suggested as a matter of practicality that dune activation conclusions based on older chronologies should be supported with modern chronological data whenever possible. In the future, if more detailed temporal stratigraphic analyses of dune fields are conducted, such as those investigating dune sedimentation rates or dune form construction events, then it will be necessary to consider whether or not to use older chronologies for comparison. For example, Wolfe and Hugenholtz (2009) documented the transformation of active barchans dunes to stabilized parabolic dunes in the Canadian Great Plains within a time span of 70 years. Chronologies that characterize dune activity in the Canadian Great Plains on a centennial scale will serve little use when attempting to correlate dune activity across the region at this high resolution.

2.5.3. Large-scale climatic considerations

A further consideration when correlating regional dune activity, especially to changes in climate, is that the sheer size of the Great Plains makes linking dune activity from one part of the region to another difficult, particularly if large climatic shifts result in synchronous change, but in opposite directions, or if climate change is time-transgressive across the region (Miao et al., 2007a; Williams et al., 2010). Dune activity from the southern Great Plains, for example, might not be expected to correlate to dune activity in the Canadian Great Plains or even the central Great Plains if only part of the Great Plains is under drought conditions. Paleoclimatic records from the northern Great Plains, for example, document regular, decadal-scale drought between 2000 and 800 years ago followed by relatively mesic conditions (e.g., Laird et al. 1996; 1998; Schmieder et al., 2011), whereas records from the southern and western U.S. show decadal-scale droughts throughout much of the last 2000 years, especially within the last 800 years (e.g., Grissino-Mayer, 1996; Cook et al., 2004; 2009). While the difference in these records may reflect local climate change, they may also reflect the time-transgressive nature of Great Plains climate. Several non-dune paleoclimatic records, for example, suggest that MCA drought did not occur at the same time in all locations. Laird et al. (1996) identified MCA droughts in the northern Great Plains between ~1000 and

~800 years ago; Schmieder et al. (2011) also reported MCA droughts in the central Great Plains between ~1000 and ~800 years ago. Records from the southwestern U.S., however, suggest that MCA droughts occurred between ~1100 and ~900 years ago (Grissino-Mayer, 1996).

This spatial complication reinforces our limited understanding as to how large-scale atmospheric changes initiate drought in the Great Plains. El Niño Southern Oscillation (ENSO) conditions have, for example, been identified as a primary cause of prehistoric North American drought, particularly in the western and southern U.S. (Herweijer et al., 2006; Seager, 2007; Seager et al., 2009; Woodhouse et al., 2009). Other researchers have suggested, however, a relationship between North American drought and variations in sea-surface temperatures in the North Atlantic Ocean, which is modeled to bring drought to the southern and central Great Plains (Feng et al., 2008). Others still have suggested that North American drought is related to changes in the Atlantic Multidecadal Oscillation (AMO) (Enfield et al, 2001; Rogers and Coleman, 2003; Sutton and Hudson, 2005; Knight et al., 2006; Shin et al., 2010) or to the Pacific Decadal Oscillation (PDO) (McCabe et al., 2004; Huang et al., 2005; Tian et al., 2006). Large-scale atmospheric-oceanic changes are likely major players in determining the magnitude and duration of Great Plains drought, and, by extension, the potential for widespread dune activity. A more in-depth understanding on the large scale atmospheric mechanism responsible for Great Plains droughts will be an added benefit when trying to correlate dune activity across the region, because it will help tease out synchronous and time-transgressive dune activity from that caused by local non-climatic factors (e.g., sediment influx, pre-historic human activity).

2.5.4. Displaying chronological data

Another limitation of existing Great Plains dune field chronologies is the manner in which they are rendered graphically in publications. The vast majority of chronological data representing dune activity in the Great Plains is reported using either probability plots, asymmetrical dot plots, or ranked dot plots, all which depict individual age data temporally (Fig. 2.8). While these three approaches remain viable ways in which to convey temporal data on dune field activity, they lack an important spatial component, i.e., specific locations where individual ages were collected. This may not be an issue when displaying chronological data from a singular small dune field (e.g., the Duncan, Hutchinson, or Abilene dunes), but, when making regional comparisons of dune activity, the spatial component of these data is crucial.

An alternative and perhaps better way of representing dune activation data is through a series of time-slice diagrams, which not only display the timing of past dune field activity, but also the location of that activity. For example, Figure 2.9 illustrates a time-slice diagram of Great Plains dune activity for the past 1200 years in 100-year intervals. Great Plains dune activity is generally limited in extent to the central Great Plains beginning ~1200 years ago, but increases dramatically during and following the MCA (~1000–700 years ago) (Fig. 2.9). Between 700 and 600 years ago dune activity once again decreases regionally, only to increase again between 600 and 400 years ago. Finally, significant dune activity is reported throughout the Great Plains within the past 300 years, which is supported by age data and historic accounts. While Figure 2.9 demonstrates the waxing and waning spatial nature of past dune activity, it similarly illustrates that North American dune fields were active for much of the past 1200 years and that dune activity during this time span is more the norm than the exception.

Similar patterns of dune activity can be seen when looking at a series of time-slice diagrams of the Great Plains for the past 18,000 years in 1000-year intervals (Fig. 2.10). Unlike a finer-resolution analysis (c.f., Fig. 2.9), this analysis highlights other important spatial aspects in the history of Great Plains dune activity. For example, Figure 2.10 illustrates the earliest reported activity for dune fields on the Great Plains, which in the case of the Canadian and northern Great Plains, is strongly linked to the retreat of the

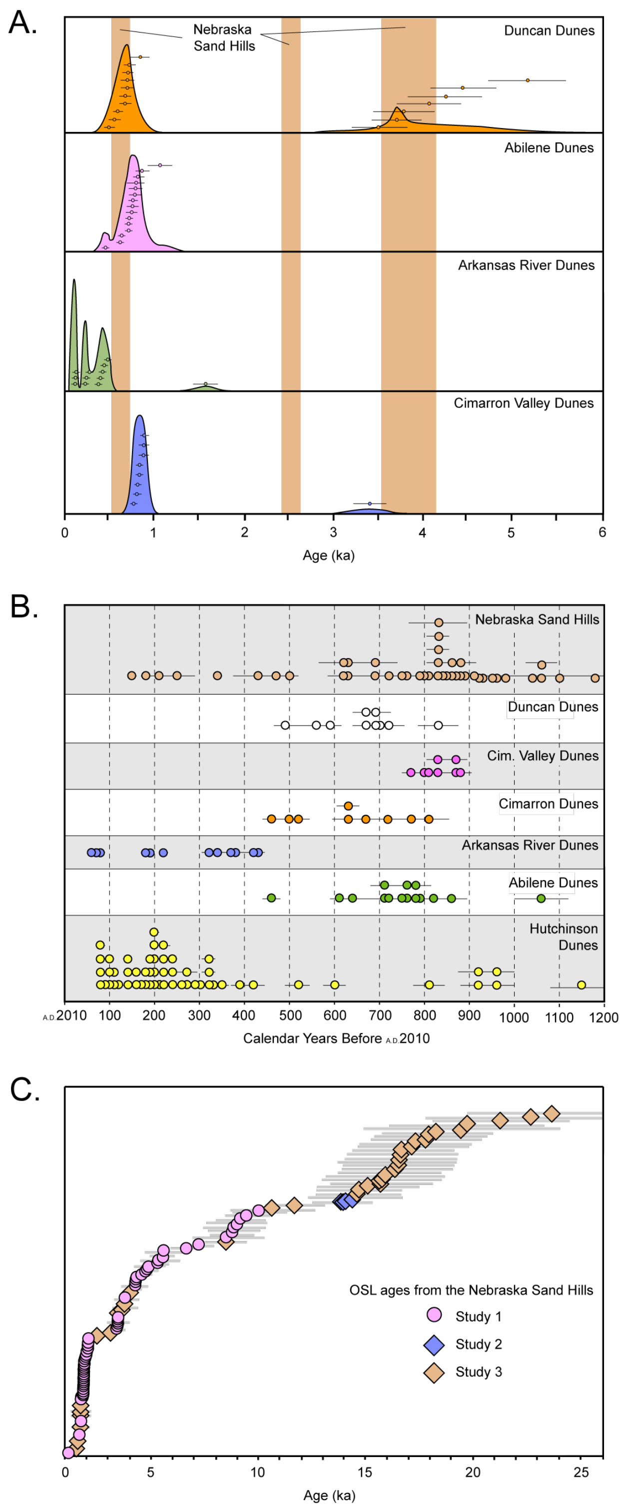


Figure 2.8. Examples of how dune chronologies have been displayed for comparison with other records reported in the literature. A) probability plots of dune field chronologies from the U.S. central Great Plains (modified from Hanson et al., 2010); B) Asymmetrical dot plots of OSL ages from dune fields in the central U.S. Great Plains (modified from Halfen et al., 2012); C) ranked dot plot of OSL from the Nebraska Sand Hills (modified from Mason et al., 2011).

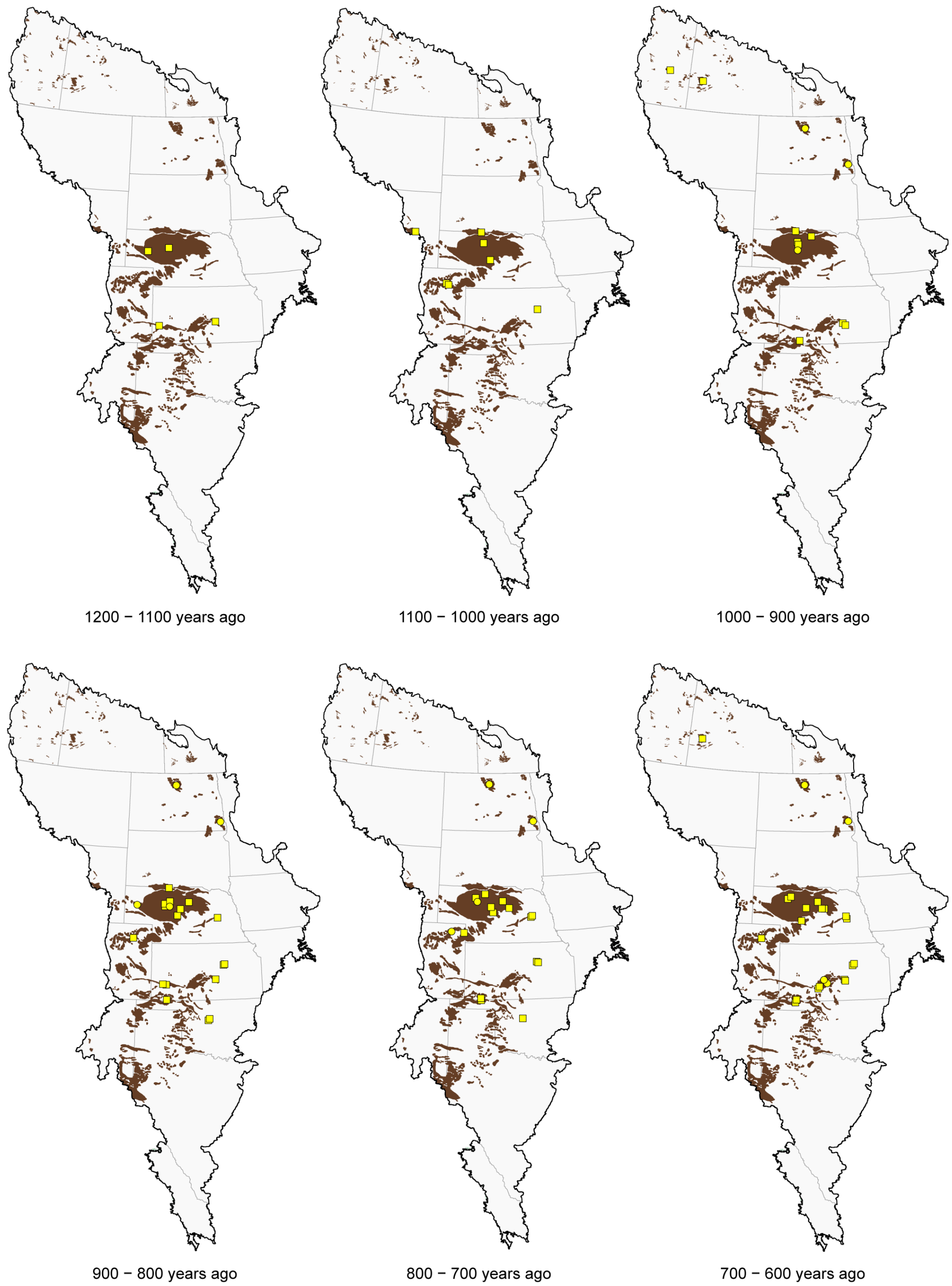
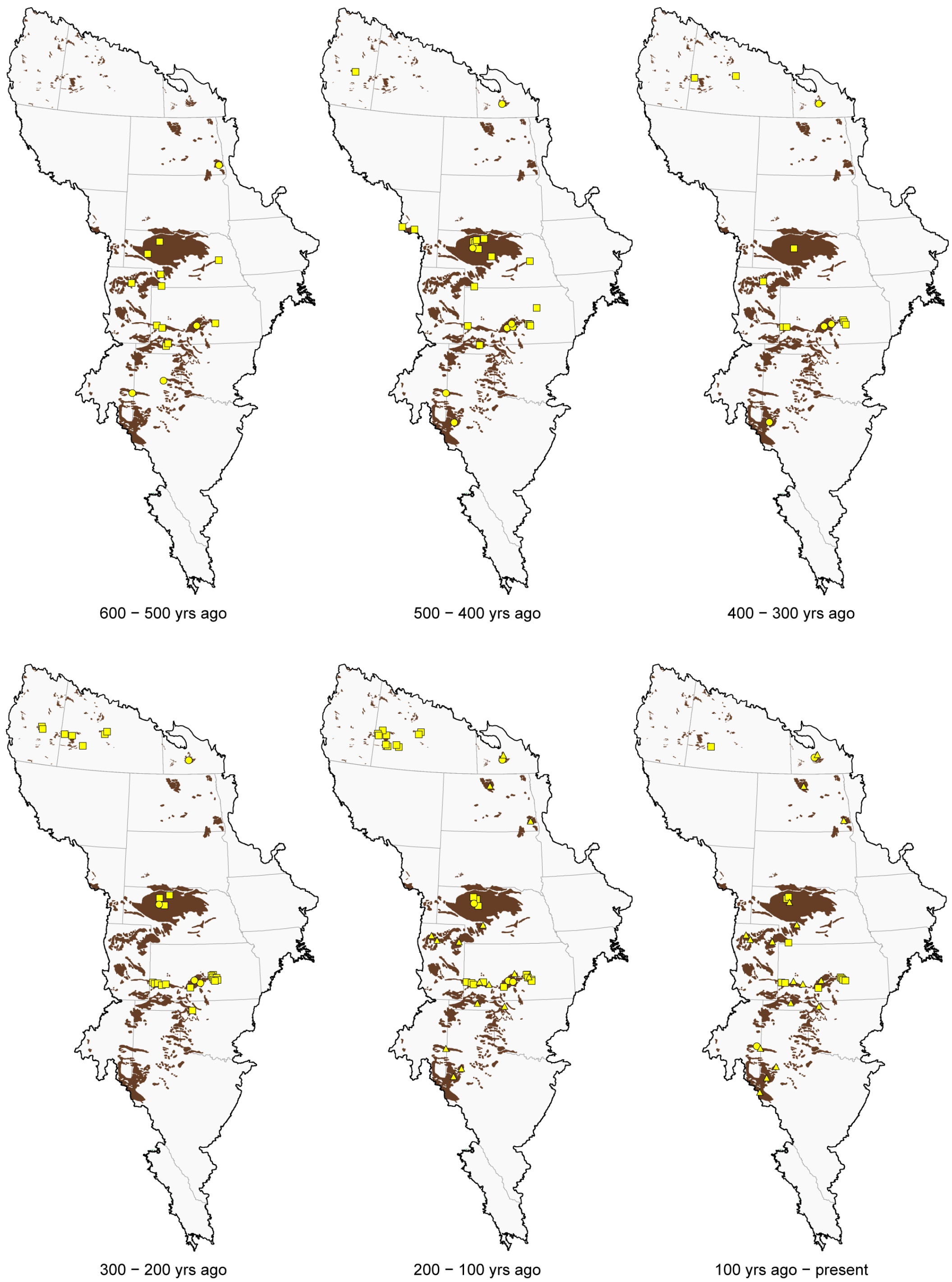


Figure 2.9. Dune activity documented for the past 1200 years (100-year time-slices) in the Great Plains. Yellow squares indicate dune activity supported by luminescence ages; yellow circles indicate dune activity bracketed by ^{14}C ages; yellow triangles indicate dune activity documented by historical records.



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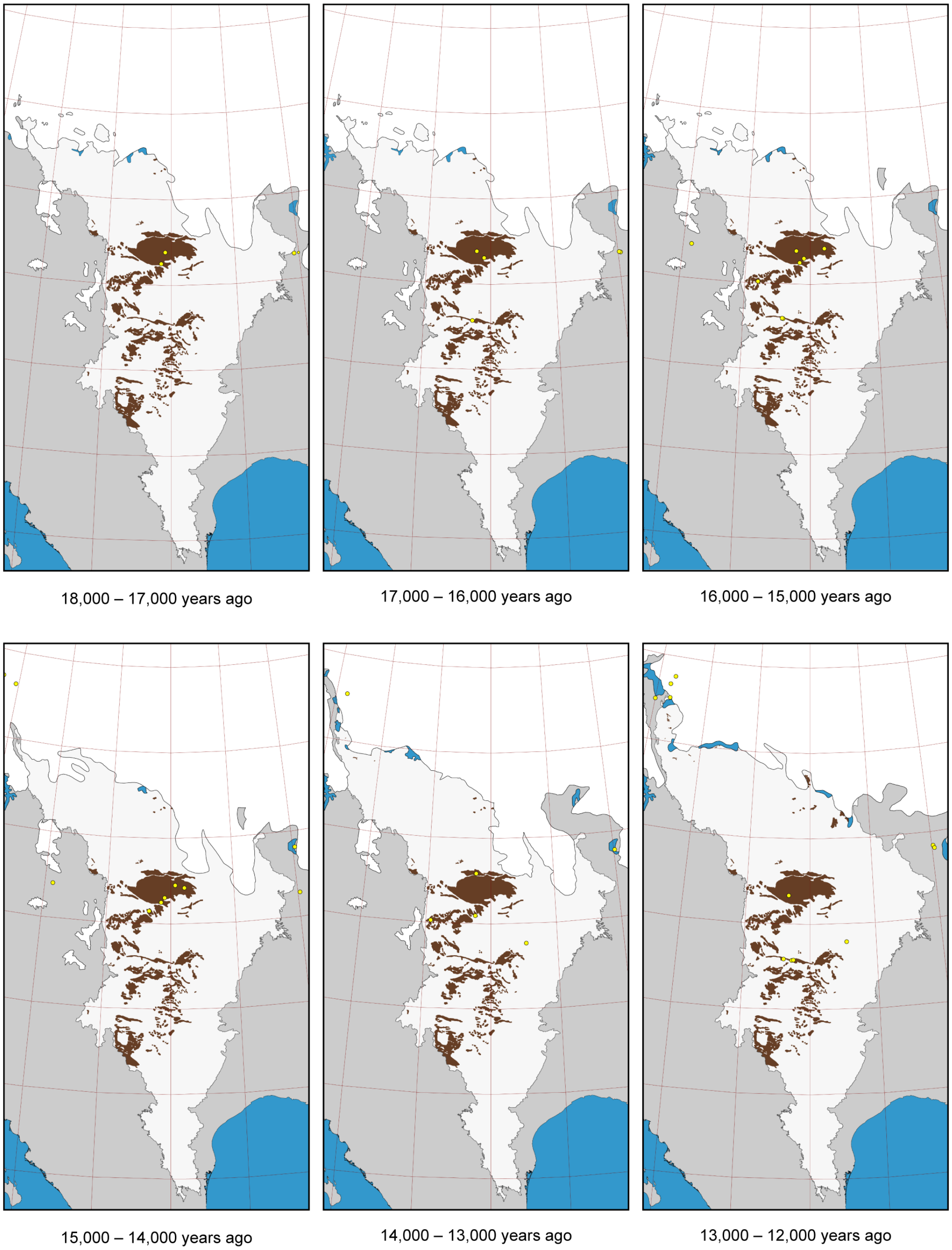
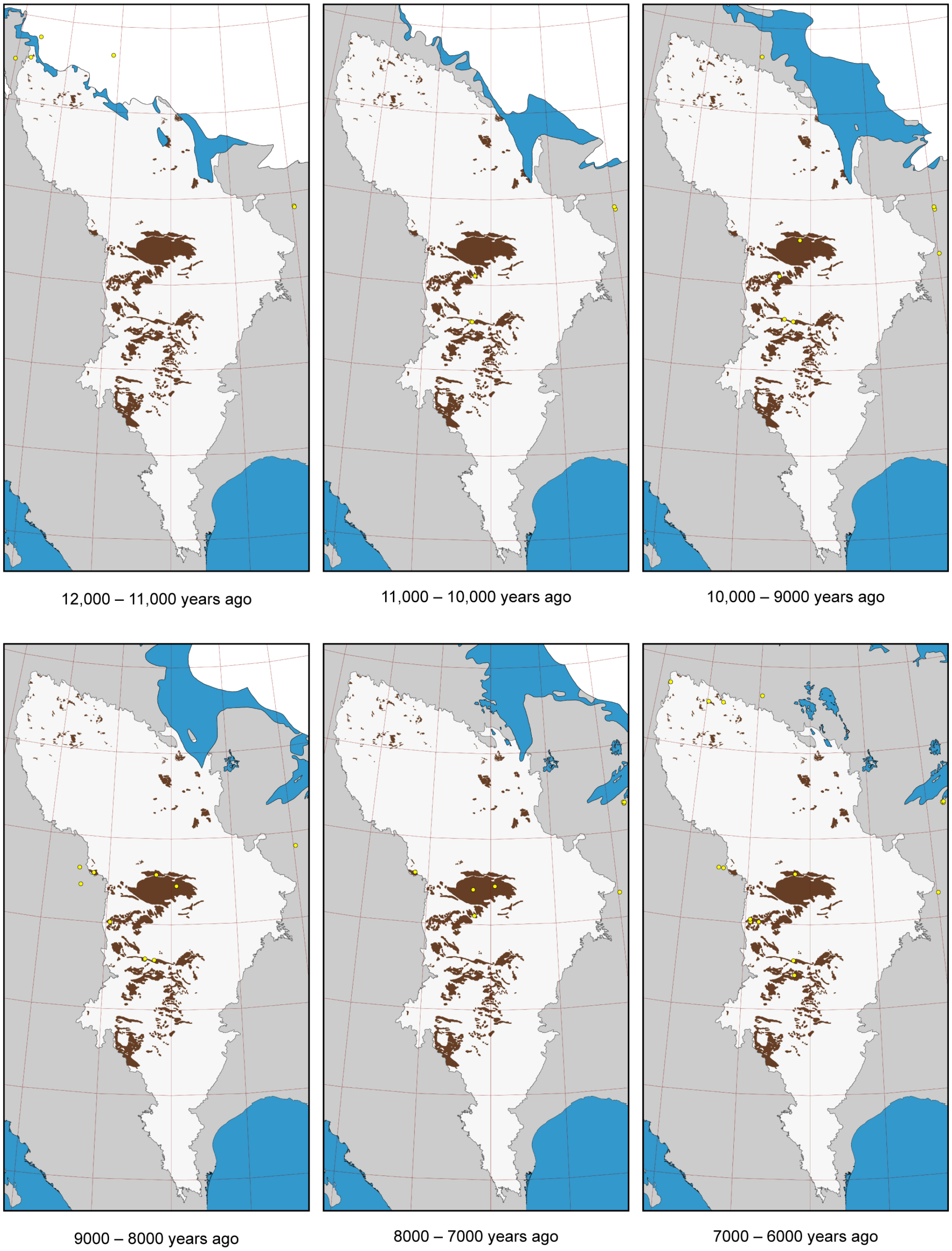


Figure 2.10. Dune activity documented for the past 18,000 years (1000-year time-slices). All ages are derived from luminescence techniques. Ice-sheet reconstructions modified from Wolfe et al., (2009).



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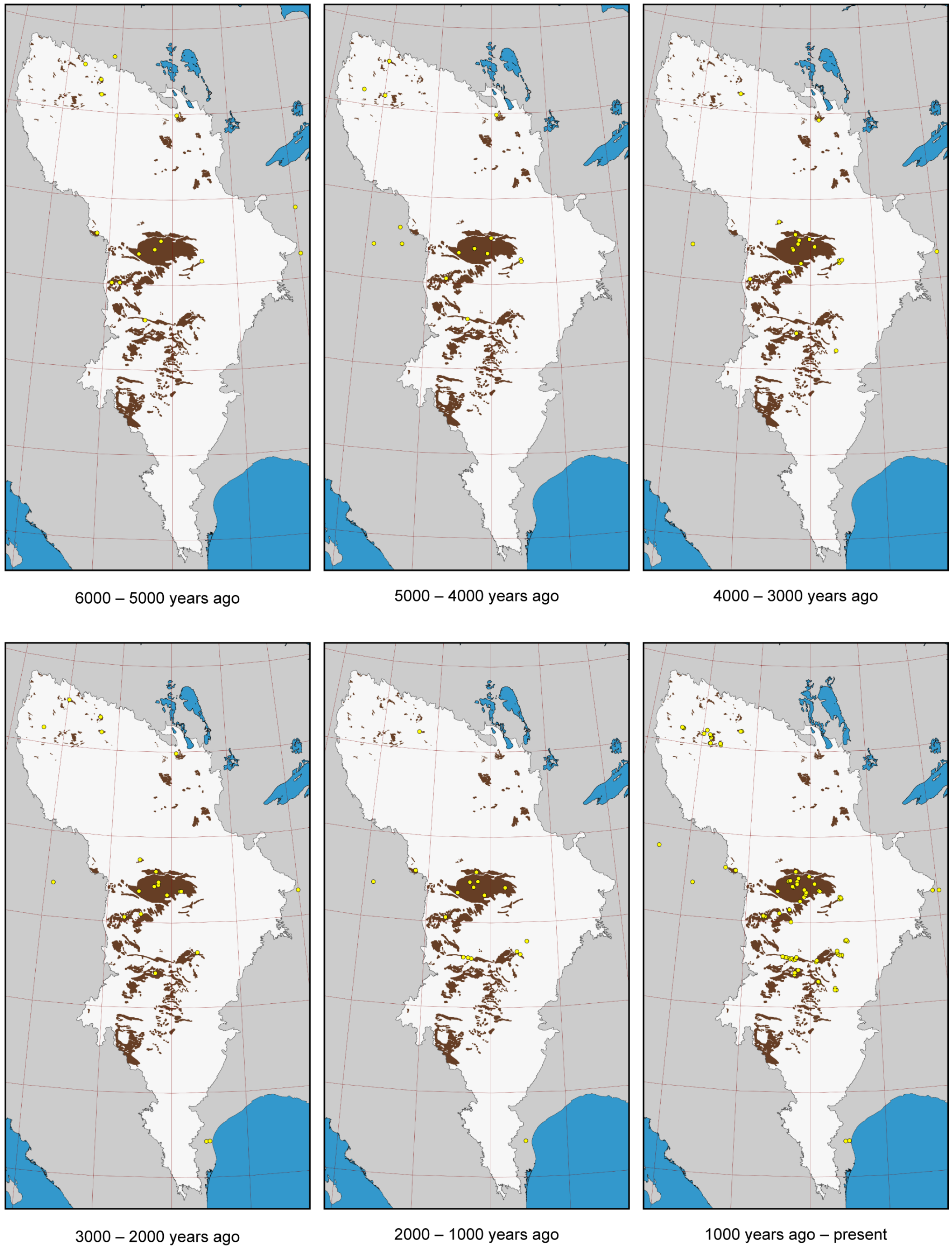

Figure 2.10 Continued. See figure caption on the previous page.

Laurentide Ice Sheet or to the deflation of glacial lake basin sediment following their drainage (e.g., Running 1995; 1996; Wolfe et al., 2004; Rawling et al., 2008). The general periods of dune activity for the past 18,000 years are also visible, such as a period of relatively stability around the Pleistocene-Holocene transition (~12,000 years ago), increased activity in the early Holocene, and widespread activity through the entire Great Plains within the past 1000 years (Fig. 2.10).

Displaying chronological data in a series of time-slice diagrams is a powerful visual tool for depicting regional dune activity, although it also highlights the gaps in spatial data and temporal bias of existing chronologies. For example, there is a lack of ages indicating dune activity in the southern Great Plains during the MCA (~1000–800 years ago) (Fig. 2.9), despite abundant paleoclimatic records suggesting the region was under drought conditions at the time (e.g., Hall, 1990; Cook et al., 2004; 2009; Hall and Penner, 2012). While it is possible a lack of ages at this time indicates dune field landscapes under environmental conditions not conducive to dune activity, it is more probable that an expanded chronological database will provide greater temporal control of past dune activity, which may inevitably show activity during the MCA.

Despite gaps in age data for some areas of the Great Plains, time-slice diagrams makes possible the comparison of dune activation ages to other spatially presented paleoclimatic data, such as gridded Palmer Drought Severity Index (PDSI) models (e.g., Cook et al., 2004; 2007; 2009). It would be expected, for example, that the geographical area of active dune fields following the MCA (Fig. 2.9) would be similar to the geographical area of drought depicted in PDSI maps, if in fact dune activity was caused by drought. Similar analyses of data from the Great Plains could potentially identify drought-related dune activity and that caused by other non-climatic factors. Furthermore, if Great Plains dune activity could be modeled with other paleoclimatic proxies, such as PDSI drought reconstruction, then dune activity could potentially be used to extend back PDSI records in the Great Plains, particularly where tree–ring records are absent.

2.6. Future research

The direction of future Great Plains dune field research is uncertain, but, based on the current status of dune field chronologies, future research on Great Plains dune fields should be focused on four specific areas: 1) enhancing map documentation of dune fields; 2) revising older, ^{14}C-based chronologies with new optical ages; 3) creating new chronologies from dune fields not yet studied; and 4) developing an increased number of and better spatially distributed non-dune paleoclimatic records.

Comprehensive and high-resolution maps are essential to future Great Plains dune field research because they will identify many smaller dune fields not yet documented in published literature. Currently, most studies providing a map of Great Plains dune fields (including this study) are modified from maps of Muhs and Holliday (1995) and Muhs and Wolfe (1999), and, while these maps accurately portray many of the larger Great Plains dune fields, they lack the resolution to depict smaller dune fields. Similarly, the polygon edges of major dune fields on these maps are not sufficiently accurate to be mapped with modern GIS-based hydrological lines and polygons, which lead to inaccurate placement of dune fields with respect to major Great Plains river systems with which they often exhibit an affinity.

High-resolution maps of aeolian dune fields available on CD-ROM and formatted for GIS applications (http://www.nrcan.gc.ca/earth-sciences) exist for Canada (Wolfe et al., 2009), however, they are not currently available for the U.S. Great Plains. Producing these maps is possible using the countywide, soil survey polygon data available through the USDA SSURGO (U.S. Department of Agriculture Soil Survey Geographical) database (http://soils.usda.gov/survey/geography/ssurgo). The SSURGO database allows users to extract soil survey polygons based on parent material criteria, such as those with aeolian sand parent material. This database has already been used to produce maps of aeolian sand and loess deposits in Wisconsin and the Upper Peninsula of Michigan (Scull and Schaetzl, 2011) and in the central Great Plains (Fig. 2.10B) (Koop et

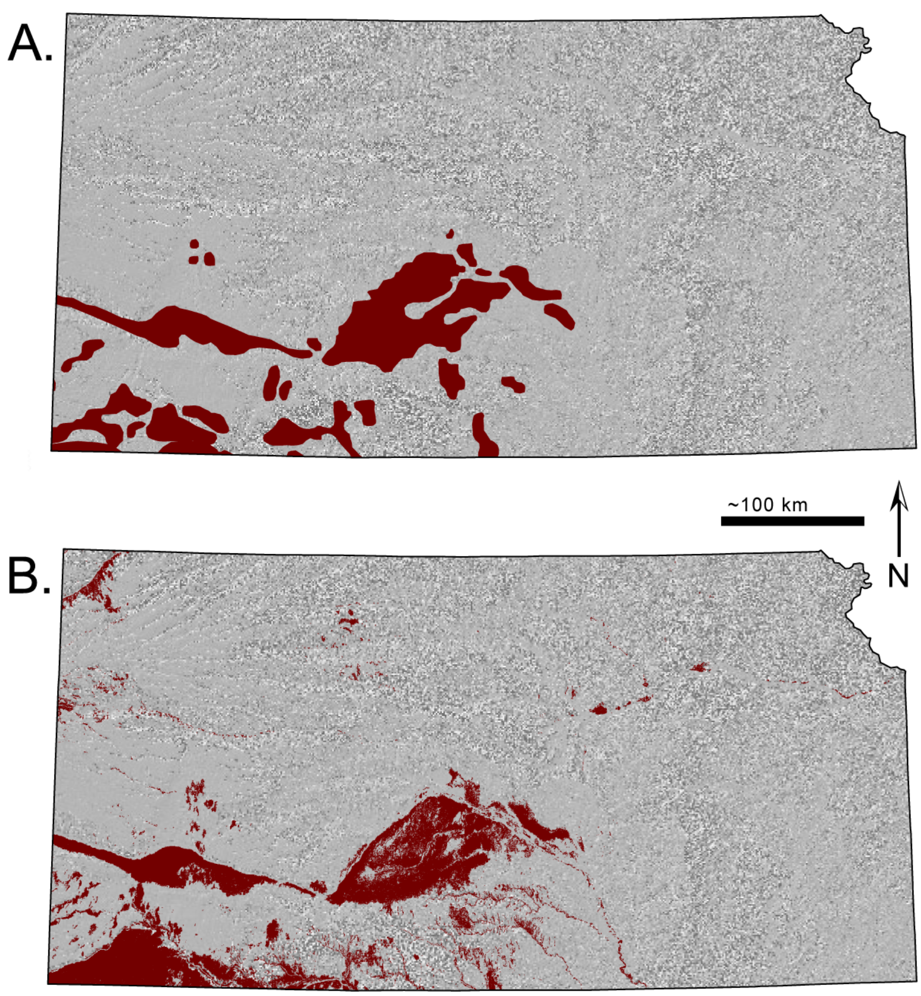

Figure 2.11—Mapped dune fields of Kansas modified from A) Muhs and Holliday (1995) and Muhs and Wolfe (1999), and B) mapped from the USDA SSURGO database (e.g., Koop et al., 2012).

al., 2012). Maps produced by Koop et al. (2012) are a significant improvement over maps redrafted from those published by Muhs and Holliday (1995) and Muhs and Wolfe (1999) (Fig. 2.10A). Despite potential errors in soil mapping, SSURGO data still provide the reliability and high resolution needed to accurately represent boundaries of Great Plains dune fields. More precise maps will also aid in the identification of new, previously un-mapped dune fields, such as those found in eastern Montana that are not yet mapped in published literature (MFG, 2012). As demonstrated by Hanson et al. (2009; 2010) and Halfen et al. (2012), smaller, isolated Great Plains dune fields have the potential to yield important chronological information that in some cases can better constrain the temporal and spatial aspects of dune activity than chronologies from larger dune fields.

A potential also exists to incorporate new, high-resolution, Great Plains dune maps into other aeolian databases, particularly the International Union for Quaternary Research Global Digital Database and Atlas of Quaternary Dune Fields and Sand Seas (dune atlas project) (http://inquadunesatlas.dri.edu). The primary objective of the dune atlas project, undertaken by leading researchers in fields of aeolian geomorphology and optical dating techniques, is to compile and make available a global database of geographically-located, chronologic information for aeolian sand deposits in desert and other inland dune fields and sand seas. Users will be able to search dune fields for information on chronology, morphology, and stratigraphy, thereby facilitating detailed regional and global comparisons of dune fields (Lancaster, 2011). The dune atlas (which includes data from Great Plains dune fields) is currently only available by in a database format by request, but will soon be public and serve as a valuable resource for those undertaking future Great Plains dune field studies.

In addition to improved mapping of dune fields, researchers should aim to re-evaluate or re-develop older ^{14}C-based dune field chronologies. It may not be necessary to review all older chronologies, such as those early studies from the Nebraska Sand Hills (e.g., Ahlbrandt et al. 1983; Loop et al., 1995) because they have since been verified by numerous luminescence chronologies. It would, however, be helpful to validate some early chronologies, such as those derived from dune fields in Colorado, Oklahoma, and Texas, which are almost exclusively derived from ^{14}C ages with only a limited number luminescence ages. The limited number of ages indicating Holocene dune activity in these areas has led to inconsistencies in their activation histories, and improved chronologies based on OSL ages may help to better resolve periods of dune activity, as well as aid in correlating dune activity in these places to that of other Great Plains dune fields. The Minot dunes (Muhs et al., 1997a) and other dune fields of the northern Great Plains are additional examples of dune fields with ^{14}C-based chronologies, which could be improved with additional OSL ages.

Future Great Plains aeolian research should focus also on development of new activation chronologies from dune fields that have not yet been evaluated for chronological information. Numerous dune fields have yet to be investigated, and, based on our assessment of the current literature, emphasis should be placed on dune fields of the southern Great Plains (Oklahoma, southeastern Colorado, New Mexico, and Texas). Dune fields in the southern Great Plains should receive attention because 1) chronological data from the southern Great Plains is significantly lacking, particular in the dune fields of Texas and Oklahoma; 2) the full geographic extent of dune fields in these areas are poorly mapped, and improved mapping will likely indicate additional aeolian sand deposits; and 3) the southern Great Plains has been the nucleus of several significant droughts in the past 70 years, including the 1950s, 1980s, late 2000s, and within the last 18 months (USDMI, 2012), and it is likely that droughts will continue to impact the region as due to future climate stress (Sivakumar, 2011).

Finally, developing an increased number of and better distributed non-dune paleoclimatic records, such as those from diatoms, tree-ring series, and stable isotope data, will greatly aid in correlating dune field activity to drought, which in turn will result in a better understanding of Great Plains climate and the way in which dune fields across the region respond to these changes. While locations that contain these proxy records are limited, recent studies have illustrated that reliable records are extractable from the Great Plains, such as the ~13,000-year record of hydrologic variability from Kettle Lake in the northern U.S. Great Plains (Grimm et al., 2011; Hobbs et al., 2011), or the 4000-year record from inter dune lakes in the Nebraska Sand Hills (Schmieder et al., 2011).

Continued recognition and exploitation of these proxy records will serve to refine and strengthen the paleoclimatic story of Great Plains dune activity.

2.7. Summary

This review has presented an overview of nearly four decades of research focused on paleoclimatic records of drought derived from Great Plains dune field activation chronologies. The earliest reported dune activity for most Great Plains dune field occurs during the latest Pleistocene and early Holocene, though several dune fields like the Nebraska Sand Hills and Arkansas River dunes appear to have formed earlier. Most dune fields show repeated activity throughout the Holocene, with the most widespread activity occurring with the last 2000 years. While localized factors, such as sediment supply and pre-historic human disturbance may have led to some dune activity, nearly all Great Plains dune field activity reported in published literature has attributed to drought. Despite this, there are still lingering questions on the exact timing and magnitudes of these droughts, in part because the exact timing of dune activity across the Great Plains has yet to be fully resolved, principally due to spatial and temporal gaps in the data. Future research on Great Plains dune fields should include higher-resolution mapping of dune fields, which would facilitate identification areas with limited data. Older ^{14}C-based chronologies should be revised with new optical ages and new chronologies developed from dune fields not yet studied. Finally, developing an increased number and better-distributed, non-dune paleoclimatic records will greatly improve our understanding of Great Plains drought and help to support those drought chronologies established based on dune activity alone.

Chapter 3

ACTIVATION HISTORY OF THE HUTCHINSON DUNES IN EAST-CENTRAL KANSAS, U.S.A., DURING THE PAST 2200 YEARS

3.1. Introduction

Dune fields of the North American Great Plains are important indicators of past drought because, during extended times of reduced moisture, vegetation cover is diminished and aeolian sedimentation ensues (Muhs and Holliday, 1995). By assigning chronologies to aeolian sedimentation events, evaluations can be made regarding the timing and extent of these droughts. This data collection is particularly important in regions like the North American Great Plains because traditional drought proxies, such as tree rings and fossil pollen, are less common in the paleoclimate record (cf., Stahle et al., 2007). Research using dune fields as indicators of drought has identified region-wide, long-term droughts from large dune fields of the Great Plains (e.g., Mason et al., 2004; Forman et al., 2005; Sridhar et al., 2006; Miao et al., 2007a). Recent emphasis, however, has focused on drought records from smaller and more peripheral dune fields of the eastern Great Plains (Hanson et al., 2009; 2010). In keeping with this approach, this study presents a new, high-resolution chronology from a small dune field along the eastern margin of the east-central Great Plains. The aim of this study, like those prior, is to determine the spatial extent of well-documented Holocene droughts. The first of these studies investigated the Duncan dunes in Nebraska (Hanson et al., 2009), and the second, the Abilene dunes in Kansas (Hanson et al., 2010) (Fig. 3.1). As with these previous studies, dating dune activity in the Hutchinson dunes will provide important spatial and temporal data on the eastward propagation of Holocene droughts previously recognized in major dune fields of the Great Plains (e.g., the Nebraska Sand Hills; Miao et al., 2007a). This study also presents the first numerical ages of dune activity in the

Hutchinson dunes and places that record within the broader context of Great Plains aeolian activity and past climate change.

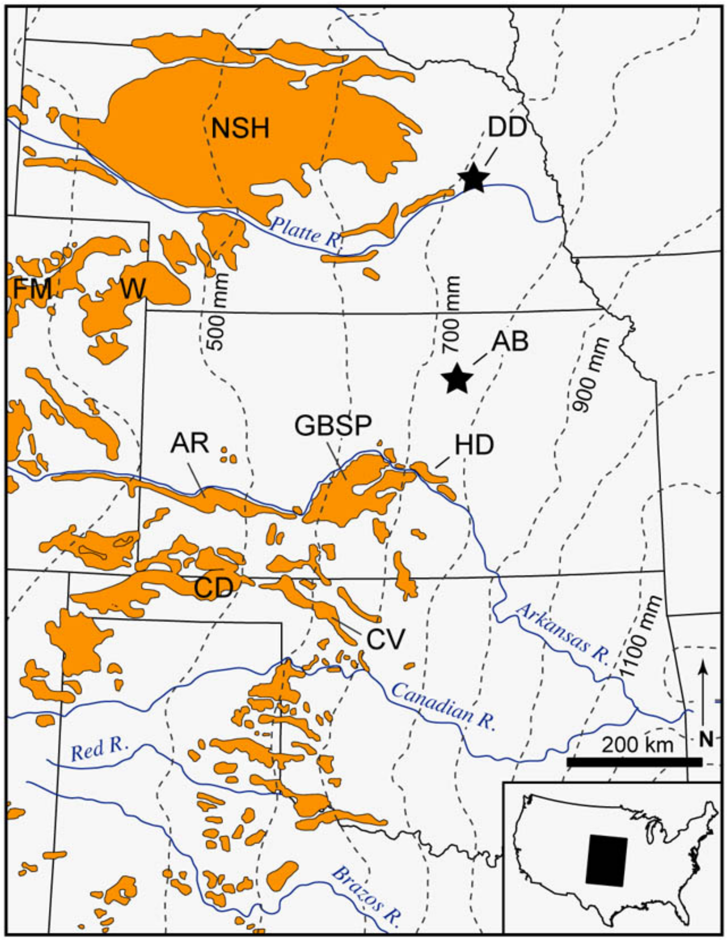

Figure 3.1. Dune fields and major river systems of the central Great Plains (modified from Wolfe et al., 2009). NSH, Nebraska Sand Hills; DD, Duncan dunes; FM, Fort Morgan dunes; W, Wray dunes (Forman et al., 2005); AB, Abilene dunes; AR, Arkansas River dunes; GBSP, Great Bend Sand Prairie; HD, Hutchinson dunes; CD, Cimarron Bend dunes; CV, Cimarron Valley dunes. Isopleths indicate mean annual precipitation (mm) based on 1961–1990 data; modified from Daly and Taylor (2009).

3.2. Previous studies

Although dune fields cover vast areas of the Great Plains, much of the aeolian-derived, regional drought record has been based on chronologies from a combination of optically stimulated luminescence (OSL) and radiocarbon dating, which for the most part have been generated from the Nebraska Sand Hills, and the Wray and Fort Morgan dunes of Colorado (e.g., Madole 1995; Forman et al., 2001; Clarke and Rendell, 2003; Goble, et al., 2004; Mason et al., 2004; Forman et al., 2005; Miao et al., 2007a; Mason et al., 2011) (Fig. 3.1). Drought-induced dune activity occurred in the Nebraska Sand Hills between ~9600 and ~6500 years ago and during events centered ~3800, ~2500, and ~700 years ago (Goble, et al., 2004; Mason et al., 2004; Miao et al., 2007a). Forman et al. (2005) also documented aeolian activity in the far western Nebraska Sand Hills ~3700, ~670, ~470, ~240, ~140, and ~70 years ago. Additionally, the Wray and Fort Morgan dunes of eastern Colorado (Fig. 3.1) were active ~540, ~420, and ~70 years ago, and ~4900, ~2400, ~1100, ~800, ~600–530, and ~370 years ago, respectively (Clarke and Rendell, 2003; Forman et al., 2005).

Less attention has been given to dunes south and east of the Nebraska Sand Hills, for example, the Arkansas River valley and the Great Bend Sand Prairie of Kansas (e.g., Arbogast, 1996; Arbogast and Johnson, 1998; Forman et al., 2008), dune fields adjacent to the Cimarron River in Oklahoma (e.g., Lepper and Scott, 2005; Werner et al., 2011), and those of the Southern High Plains (Holiday 1997; 2001) (Fig. 3.1). Radiocarbon dating of buried soils in the Great Bend Sand Prairie, Kansas (Fig. 3.1), indicated periods of dune stability ~6700, ~3700, ~2300, ~1400, ~1100, ~700, and ~300 years ago (Arbogast, 1996; Arbogast and Johnson, 1998)—each of these periods of stability was followed by aeolian activity. Forman et al. (2008) recognized dune activity within the Arkansas River dunes ~1500, ~430, ~380–320, ~180, and ~70 years ago, and, in the Cimarron River valley of west-central Oklahoma and west-central Kansas, dunes were activated ~900–700 years ago (Lepper and Scott, 2005) and ~800–400 years ago (Werner et al., 2011) (Fig. 3.1). Aeolian activity on the Southern High Plains occurred in the Muleshoe dunes after ~1,300, ~700, ~500 years ago, in the Lea-Yoakum dunes following ~3,400 years ago, in the Andrews dunes after ~2,300 years ago, and in the Seminole sandsheet between ~400 and ~300 years ago (Holliday, 2001). Additionally, all dune fields studied by Holliday (2001) were active within the last 200 years.

Several smaller dune fields lie on the eastern margin of the Great Plains (Fig. 3.1). The Duncan dunes in the eastern Platte River valley, Nebraska were active ~4300–3500 years ago and ~900–500 years ago (Hanson et al., 2009), and a companion study of the Abilene dunes (Hanson et al. 2010) documented activation at ~1100–500 years ago. The latter periods of activity from both the Duncan and Abilene dunes correspond very well with regional dune field records, including those from the Nebraska Sand Hills (Miao et al., 2007a) and from other dune fields in Kansas and Oklahoma (Arbogast, 1996; Arbogast and Johnson, 1998; Lepper and Scott; 2005; Werner et al., 2011).

In addition to paleoclimatic records derived from dune field activity, some data exist from other Great Plains drought proxies, though these data at times are limited in spatial coverage and in some instances, such as lake sediments, are of coarser resolution with less accurate temporal control (Woodhouse and Overpeck, 1998). Nevertheless, drought identified in available records generally correlates well with Great Plains aeolian activation records. Schmieder et al. (2011), for example, provided a 4000-year record of drought from the Nebraska Sand Hills. These investigators contended that drought activity prior to 2000 years ago was more prevalent, but, they also documented both the MCA megadrought and many smaller "minidroughts" within the lass 2000 years. Further, they attempted to correlate dune activity in the Nebraska Sand Hills with their drought record and concluded that many Holocene minidroughts recorded in the lake records are not present in the aeolian record.

Laird et al. (1996) documented four Holocene hydrological periods in Moon Lake, North Dakota: 1) a transitional period from glacial conditions to the earliest Holocene; 2) dry conditions during the mid Holocene ~7300–4700 years ago; 3) another transitional period between 4700 and 2200 years ago; and 4) a period of increased, but variable, aridity during the past 2200 years. While recognizing variability during the past

2200 years, Laird et al. (1996) also documented specific increases in aridity during the Medieval Climatic Anomaly (MCA). Similarly, Fritz et al. (1994) reported aridity in North Dakota during the Little Ice Age (LIA).

Using lake-water salinity records from North Dakota, Fritz et al. (2000) documented highly variable climate during the past 2000 years and argued specifically that the MCA and LIA were hydrologically complex, though they also argued that the changes in moisture documented during the MCA and LIA differed little from those recorded in the longer-term hydrological patterns of the Great Plains. Most recently, Hobbs et al. (2011), using diatoms to reconstruct lake salinity records from Kettle Lake, North Dakota, reported several episodes of aridity following ~8400, ~4400, and ~870 years ago in the northern Great Plains.

Rapid channel incision, which results from greater surface runoff due to less vegetation cover, has provided another drought proxy for the Great Plains. Incision events corresponding to the MCA were reported for multiple basins of the southern Great Plains by Hall (1990) and in the Republican River basin of southern Nebraska by Daniels and Knox (2005). Tree-ring series from the western United States have also provided useful paleoclimate data on the timing of recent drought episodes (e.g., Grissino-Mayer, 1996; Cook et al., 2004; Cook et al., 2007). Specifically, Cook et al. (2004) recognized widespread drought ~1100–700 years ago, an interval that matches the timing of the MCA. Cook et al. (2007) also documented drought in the Mississippi River valley ~1000, ~900–750, and ~650–600 years ago.

3.3. Study Area

The Hutchinson dunes are a small, crescentic-shaped dune field northeast of the “Big Bend” in the Arkansas River valley (Figs. 3.1; 3.2). Collectively, the Hutchinson dunes are comprised of a main dune field and adjacent isolated dune areas around its periphery (Fig. 3.2). The main dune field lies atop a Pleistocene terrace deposits ~18 m

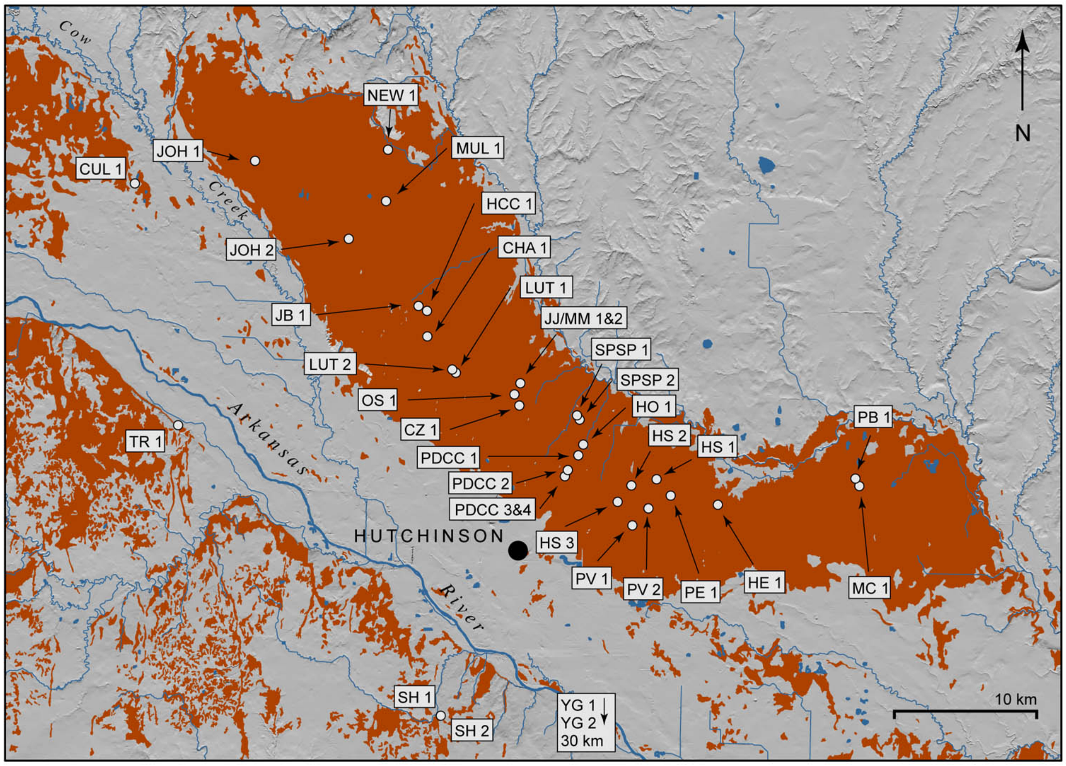

Figure 3.2. The Hutchinson dunes and OSL sample sites.

above the modern Arkansas River, which itself is underlain by Permian bedrock, predominantly the Ninnescah shale and Harper sandstone (Bayne, 1956)

Dunes average ~8 m in relief, have weekly developed surface soils (<20 cm of A horizon development), and consist of fine to medium-coarse sand (250–750 μm). Though specific dune forms are not distinguishable in most cases, some of the larger dunes have complex parabolic morphologies, which indicate that sand was mobilized under a southwesterly wind regime. Presently, the dunes are completely stabilized by mixed, tall-short-grass prairie vegetation (e.g., Andropogon hallii, Calamovilfa longifolia, Prunus angustifolia). Interdune areas are commonly filled with water following rain, which remains perched due to the fine-grained terrace deposits located immediately below the dune sediments (Fig. 3.3). The sediment source for the Hutchinson dunes is likely deflated alluvium from the Arkansas River since the sediment size of other possible

Figure 3.3. Aerial view of the Hutchinson dunes illustrating the stability and hummocky dune morphology found throughout the dune field (Sites SPSP 1, 2: Fig. 3.2). Interdune areas have high water tables and often standing water where the dune field overlies the fine-grained terrace fill.

alluvial sources are too fine to produce the sediment found in the dune field (Bayne, 1956). Based on this source location, initial dune field formation occurred when winds were from the south-southwest. In contrast, the Great Bend Sand Prairie and the Arkansas River dunes formed south of the Arkansas River when dominant winds were from the north and northwest (Simonett, 1960; Arbogast and Muhs, 2000) (Fig. 3.1).

The location of the Hutchinson dunes is important in testing the spatial patterns of regional drought activity because they lay on the eastern edge of a steep east-west precipitation gradient. Precipitation records indicate that the Hutchinson dunes receive ~770 mm precipitation annually, whereas the western edge of the Arkansas River dunes, only 360 km west, receive ~450 mm annually (HPRCC, 2012). The Hutchinson dunes also occur in proximity to several other studied dune fields, e.g., the Great Bend Sand Prairie is ~50 km southwest, the Abilene and Duncan dunes are ~90 km and ~365 km north, respectively, and the Cimarron Valley dunes are ~250 km south (Fig. 3.1).

3.4. Methods

Sixty-six samples collected from 35 sites (Table 3.1) in the Hutchinson dunes were analyzed using OSL dating (Fig. 3.1; Table 3.2). The majority of samples were collected from the crests and side slopes of completely stabilized sand dunes by vertical hand auguring with additional samples collected from profiles created in sand and gravel quarries, road cuts, and natural exposures. Dated sediment was collected in 20 cm long sections of 5 cm diameter steel conduit inserted into a full auger bucket or profile face. Sediment was packed tightly in the tubes, and then capped and sealed to prevent shifting of sediment during transport. Samples were not taken within 1 m of the surface in order to avoid potentially young ages due to soil-related bioturbation. In addition to the 66 sampled for OSL dating, one bulk organic sample from a buried A horizon was collected for AMS ^{14}C dating, and the age was calibrated using Calib 6.1.0 (Stuiver and Reimer, 1993).

OSL dating was conducted at the University of Nebraska Luminescence and Geochronology Laboratory, using procedures similar to those of Hanson et al. (2010). Samples were removed from the collection tubes in the laboratory, and the outer ~5 cm of each end was discarded. Samples were sieved to isolate 90–150 μm grains and then treated with 1 N HCl to remove carbonates and then floated in a 2.7 g cm^{-3} sodium polytungstate solution to remove heavy minerals. The floated grains were subsequently treated with 48% HF for ~75 minutes to remove feldspars and to etch quartz grains,

Table 3.1. Hutchinson dunes sample sites

Field Site	Site Code	Latitude (dd)	Longitude (dd)
Highlands Site	HCC 1	38.17340	-97.94438
Prairie Dunes 1	PDCC 1	38.08820	-97.85469
Prairie Dunes 2	PDCC 2	38.08990	-97.85413
Prairie Dunes 3	PDCC 3	38.09828	-97.84660
Prairie Dunes 4	PDCC 4	38.84660	-97.84798
Sand Hills 1	SPSP 1	38.11772	-97.95760
Sand Hills 2	SPSP 2	38.11862	-97.84795
Young 1	YG 1	37.74697	-98.05980
Young 2	YG 2	37.74673	-98.06013
Showalter 1	SH 1	37.96647	-97.93683
Showalter 2	SH 2	38.12083	-98.10553
Trostle	TR 1	38.12083	-98.10552
Jarrott 1	JJ 1	38.13332	-97.88353
Jarrot 2	JJ 2	38.13343	-97.88293
Holland	HO 1	38.10362	-97.84430
McCury	MC 1	38.08074	-97.66496
Prairie Bell	PB 1	38.08378	-97.66672
Oswald	OS 1	38.12993	-97.88686
Pease	PE 1	38.07705	-97.78754
Czarnek 1	CZ 1	38.12388	-97.88540
Czarnek 2	CZ 2	38.12408	-97.88572
Czarnek 3	CZ 3	38.12412	-97.88577
Swanson 1	HS 1	38.07388	-97.82223
Swanson 2	HS 2	38.08207	-97.81297
Swanson 3	HS 3	38.08512	-97.79575
Voth 1	PV 1	38.06127	-97.81242
Voth 2	PV 2	38.07027	-97.80205
Epps	HE 1	38.07230	-97.75690
Buttler	JB 1	38.17557	-97.95008
Mull	MUL 1	38.23001	-97.97059
Cullop	CUL 1	38.23206	-98.11646
Johnson 1	JOH 1	38.25127	-98.05504
Johnson 2	JOH 2	38.21102	-97.99519
Luttgen 1	LUT 1	38.14207	-97.92794
Luttgen 2	LUT 2	38.14271	-97.92803
Newfield	NEW 1	38.25618	-97.96818
Chalfant	CHA 1	38.15673	-97.94525

followed by a treatment in 47% HCl for 30 minutes. Finally, samples were re-sieved to remove grains finer than 90 μm. Equivalent dose (D_e) values were determined using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000) on aliquots containing ~1200–800 quartz grains. Five regenerative doses were used including a zero dose and a repeated initial dose. Individual aliquots were rejected if their recycling ratios were >±10%, or if they had measurable signals during exposure to infrared diodes. Aliquots were also rejected if their equivalent dose D_e values were >4σ from the mean D_e value.

Final age estimates were calculated using the mean D_e values from at least 18 accepted aliquots. Dose rate estimates were based on elemental concentrations of bulk sediment taken immediately adjacent to the OSL sample. These samples were analyzed for concentrations of K, U, Th, and Rb using high-resolution gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), or atomic emission spectroscopy (ICP-AES). The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and final dose rate values were calculated using equations from Aitken (1998). All OSL ages (Table 3.2) are presented in calendar years before 2010 (see Appendix III for representative D_e distributions, OSL growth curves, and natural shine-down curves).

3.5. Results

In general, dune stratigraphies were consistent throughout the dune field and were characterized by weakly developed surface soils (<20 cm), an absence of buried soils, and lack of other discernable changes except for various changes in moisture content—at some localities, the underlying alluvial sediment was reached (see Figs. 3.4–3.6). Exceptions were documented at the Cullop site (see: 3.5.2.1), Trostle site (see: 3.5.2.2), and alluvial sites (see: 3.5.2.3). OSL dating yielded good results except for one sample, and ages cluster into three groups: 1) underlying alluvial sediments deposited prior to ~90,000–60,000 years ago, 2) loess mantling alluvium, which was deposited prior to ~77,000 years ago, and 3) three periods of aeolian activity at ~2100–1800 years ago, ~1,000–900 years ago, and that after ~600 years ago (Table 3.2). Core profiles, including OSL sample depths for individual dune sites, are presented in Figures 3.4–3.6.

Table 3.2: Equivalent dose, dose rate, and age estimates for the Hutchinson dunes

OSL Sample	UNL Lab #	Depth (m)	U[a]	Th[b]	K2O (wt%)	H_2O (%)[c]	Dose rt. (Gy/ka)	De (Gy) ± 1 Std. Err.	Optical age ± 1σ
Highlands Country Club									
HCC 1-1	1874	3.15	0.8	3.6	2.4	3.1	2.45 ± 0.16	0.67 ± 0.04	270 ± 30
HCC 1-2	1875	2.7	0.7	2.9	2.6	2.3	2.54 ± 0.17	0.82 ± 0.12	320 ± 50
HCC 1-3	1876	9.75	0.6	2.6	2.4	3.4	2.22 ± 0.16	0.72 ± 0.07	330 ± 40
Prairie Dunes Country Club Site 1									
PDCC 1-1	1877	1.32	0.6	2.6	2.7	1.4	2.61 ± 0.17	1.16 ± 0.09	450 ± 50
PDCC 1-2	1878	4.04	0.6	2.7	2.5	2.7	2.35 ± 0.16	0.74 ± 0.03	320 ± 30
PDCC 1-3	1879	6.69	0.7	3.1	2.3	5	2.21 ± 0.17	0.71 ± 0.03	320 ± 30
Prairie Dunes Country Club Site 2									
PDCC 2-1	1880	2.77	0.9	3.7	2.4	12.6	2.25 ± 0.26	2.59 ± 0.05	1150 ± 140
Prairie Dunes Country Club Site 3									
PDCC 3-1	2091	1.8	0.7	2.7	2.6	4.6	2.46 ± 0.18	0.30 ± 0.01	120 ± 10
PDCC 3-2	2092	7.7	0.8	3.4	2.8	1.6	2.67 ± 0.17	1.03 ± 0.10	390 ± 50
Prairie Dunes Country Club Site 4									
PDCC 4-1	2093	4.2	1.1	4.7	2.5	9.8	2.47 ± 0.17	> 150	> 61,000[e]
Sand Hills State Park Site 1									
SPSP 1-1	1881	1.4	0.9	3.7	2.6	1.6	2.66 ± 0.16	0.77 ± 0.01	290 ± 20
SPSP 1-2	1882	7.1	0.8	3.2	2.6	4	2.43 ± 0.17	2.24 ± 0.07	920 ± 80
Sand Hills State Park Site 2									
SPSP 2-1	1883	2.4	0.7	3	2.5	1.2	2.49 ± 0.16	0.75 ± 0.02	300 ± 30
SPSP 2-2	2090	7.4	0.6	2.4	2.7	3.8	2.40 ± 0.18	0.83 ± 0.02	350 ± 30
Young Site 1									
YG 1-1	2180	2.1	0.8	4.1	2.5	6.3	2.47 ± 0.14	> 220	> 89,000[e]
Young Site 2									
YG 2-1	2181	1.65	0.8	3.4	3	2.2	2.92 ± 0.11	> 220	> 75,000[e]

Showalter Site 1									
SH 1-1	2182	1	2	10	2.4	13.4	2.89 ± 0.29	> 190	> 66,000[e]
Showalter Site 2									
SH 2-1	2183	1	1.5	7.1	2.4	11.2	2.63 ± 0.23	> 160	> 60,000[e]
Trostle Site									
TR 1-1	2184	2.13	2.4	9.8	2.2	9.9	2.86 ± 0.21	> 220	> 77,000[e]
Jarrott Site 1									
JJ 1-1	2553	1.6	3.2	3	2.9	2	3.39 ± 0.20	0.59 ± 0.02	180 ± 10
JJ 1-2	2554	6.15	2.5	3.6	2.9	5.1	3.08 ± 0.22	0.62 ± 0.02	200 ± 20
Jarrott Site 2									
JJ 2-1	2555	1.6	2.6	3.4	2.8	2.5	3.20 ± 0.19	0.55 ± 0.04	170 ± 20
Holland Site									
HO 1-1	2562	1.6	3.5	5.1	2.7	2.8	3.43 ± 0.20	0.33 ± 0.01	100 ± 10
HO 1-2	2563	6.33	3.8	3.3	2.9	4.4	3.40 ± 0.22	1.78 ± 1.20	520 ± 50
McCury Site									
MC 1-1	2560	1.63	4.6	4.7	2.7	4.4	3.61 ± 0.22	0.29 ± 0.03	80 ± 10
MC 1-2	2561	5.85	2.6	2.7	2.8	17.7	2.63 ± 0.40	0.38 ± 0.03	140 ± 30
Prairie Bell Angus Site									
PB 1-1	2558	1.8	2.4	2.7	2.8	3.9	3.06 ± 0.20	0.33 ± 0.01	110 ± 10
PB 1-2	2559	6.26	1.2	2.9	2.9	2	2.79 ± 0.18	0.62 ± 0.04	220 ± 20
Oswald Site									
OS 1-1	2556	1.73	2.4	2.8	2.8	1.4	3.15 ± 0.18	0.25 ± 0.02	80 ± 80
OS 1-2	2557	6.23	2.6	3.2	2.6	3.3	2.92 ± 0.18	0.47 ± 0.03	160 ± 20
Pease Site									
PE 1-1	2551	1.63	4.8	3.5	2.8	4.7	3.64 ± 0.23	0.64 ± 0.03	180 ± 20
PE 1-2	2552	6.23	4.7	3.8	2.8	4.4	3.54 ± 0.22	0.66 ± 0.05	190 ± 20
Czarnek Site 1									
CZ 1-1	2686	1.72	0.8	3.6	2.9	6.7	2.71 ± 0.22	0.55 ± 0.02	200 ± 20
CZ 1-2	2687	7.42	1.1	2.2	2.9	4.4	2.67 ± 0.20	0.63 ± 0.02	240 ± 20
Czarnek Site 2									
CZ 2-1	2688	6.65	1.3	4.7	2.8	5.8	2.78 ± 0.20	0.73 ± 0.02	260 ± 30
Czarnek Site 3									
CZ 3-1	2689	5.43	0.9	2.6	2.9	4	2.72 ± 0.19	0.55 ± 0.03	200 ± 20
Swanson Site 1									
HS 1-1	2692	1.91	0.8	3.5	3	3.1	2.85 ± 0.19	0.62 ± 0.02	220 ± 20
HS 1-2	2693	5.71	1.1	4.8	2.9	11	2.65 ± 0.03	0.62 ± 0.03	240 ± 30

Swanson Site 2									
HS 2-1	2694	1.74	1.5	4.6	2.9	5.4	2.98 ± 0.22	2.86 ± 0.03	960 ± 80
HS 2-2	2695	6.98	1.3	4.2	2.9	4.6	2.86 ± 0.21	2.75 ± 0.03	960 ± 80
Swanson Site 3									
HS 3-1	2696	1.83	0.6	3.1	2.8	5.2	2.61 ± 0.20	0.25 ± 0.01	100 ± 10
HS 3-2	2697	7.02	0.8	2.9	3	3.1	2.77 ± 0.19	1.67 ± 0.02	600 ± 50
Voth Site 1									
PV 1-1	2700	1.78	1.7	3.7	3.1	7	3.03 ± 0.25	0.73 ± 0.02	240 ± 20
PV 1-2	2701	6.9	0.9	2.7	2.9	5.3	2.65 ± 0.21	2.45 ± 0.08	920 ± 90
Voth Site 2									
PV 2-1	2702	1.74	0.9	3.8	2.9	2.5	2.90 ± 0.19	0.56 ± 0.02	190 ± 20
PV 2-2	2703	6.45	1	4.7	2.9	8.5	2.70 ± 0.25	1.13 ± 0.07	420 ± 50
Epps Site									
HE 1-1	2690	1.98	0.6	2.6	2.6	7.4	2.36 ± 0.20	0.51 ± 0.03	220 ± 20
HE 1-2	2691	6.9	0.9	2.7	2.9	3.6	2.71 ± 0.19	0.53 ± 0.02	200 ± 20
Buttler Site									
JB 1-1	2698	1.75	0.6	2.9	2.9	5.4	2.65 ± 0.21	0.21 ± 0.01	80 ± 10
JB 2-1	2699	7	1.5	2.8	2.9	5	2.77 ± 0.21	0.52 ± 0.02	190 ± 20
Mull Site									
MUL 1-1	2984	2.09	0.6	2.5	2.7	2.4	2.53 ± 0.17	0.34 ± 0.02	140 ± 10
MUL 1-2	2985	6.38	0.6	2.6	2.7	4	2.43 ± 0.18	0.34 ± 0.02	140 ± 20
MUL 1-3	2986	6.58	0.7	2.6	2.7	15.9	2.16 ± 0.32	0.47 ± 0.01	220 ± 30
Cullop Site									
CUL 1-1	2971	1.8	1.2	5.3	2.9	6.9	2.91 ± 0.23	5.96 ± 0.09	2050 ± 190
CUL 1-2	2972	5.34	1.2	5.3	2.9	7.9	2.84 ± 0.25	5.92 ± 0.09	2080 ± 200
Johnson Site 1									
JOH 1-1	2974	1.87	0.7	2.9	2.7	7	2.49 ± 0.21	4.69 ± 0.16	1880 ± 190
JOH 1-2	2975	4.25	0.7	3	2.7	7.2	2.42 ± 0.21	5.00 ± 0.10	2070 ± 200
Johnson Site 2									
JOH 2-1	2976	1.69	0.7	2.6	2.8	4.7	2.58 ± 0.19	0.54 ± 0.01	210 ± 20
JOH 2-2	2977	5.08	0.7	3.1	2.7	19.9	2.15 ± 0.37	0.57 ± 0.02	270 ± 50
Luttgen Site 1									
LUT 1-1	2981	1.86	0.7	3.1	2.7	6.4	2.50 ± 0.20	0.19 ± 0.01	80 ± 10
LUT 1-2	2982	6.55	0.8	3.3	2.6	5.7	2.44 ± 0.19	0.38 ± 0.02	160 ± 20
Luttgen Site 2									
LUT 2-1	2983	2.12	0.7	2.6	2.7	7.1	2.48 ± 0.21	0.22 ± 0.02	90 ± 10

Newfield Site									
NEW 1-1	2987	2.07	0.6	2.3	2.7	4	2.52 ± 0.18	0.26 ± 0.01	100 ± 10
NEW 1-2	2988	6.8	0.5	2.1	2.7	5.8	2.33 ± 0.19	0.46 ± 0.02	200 ± 20
Chalfant Site									
CHA 1-1	2969	1.85	0.6	2.7	2.7	4.5	2.51 ± 0.19	0.27 ± 0.01	110 ± 10
CHA 1-2	2970	7.05	0.6	2.5	2.7	3.3	2.56 ± 0.17	2.08 ± 0.06	810 ± 70

[a] Uranium (ppm).
[b] Thorium (ppm).
[c] Assumes 100% error in measurement.
[e] Sample was too old to produce a meaningful age; this is considered a minimum age estimate.

3.5.1. Dune ages from the Hutchinson dunes

To facilitate discussion of the age results, the Hutchinson dunes have been divided into three sections: northwest (Fig. 3.4), central (Fig. 3.5), and southeast (Fig. 3.6). In the northwest, the majority of dune ages fall into the period of most recent activity (~600–70 years ago). One exception is the Johnson 1 site (JOH 1, Fig. 3.4), where dune ages of 2070 ± 200 years ago (JOH 1-2) and 1880 ± 190 years ago (JOH 1-1) were obtained. While most ages from shallow samples (< 3 m) reflect dune activity during late 19th or early 20th century droughts (possibly 1910s and 1930s droughts), deeper samples are older, ranging in age between 810 ± 10 (CHA 1-2) and 160 ± 20 (LUT 1-2).

Dune ages in the central dune field are consistent with those of the northwestern section (Fig. 3.5). Less historic dune activity was detected in the area, and the majority of activity occurred after ~600 years ago, with only two ages occurring outside this period of activity (e.g., PDCC 2-1, 1150 ± 140; SPSP 1-2, 920 ± 80). Lastly, dune ages from the southeastern dune field are in agreement with ages from the central and northwestern dune field, once again showing dominance of dune activity after ~600 years ago (Fig. 3.6). Like ages from the central dune field, only three ages from the southeastern dune field fall outside this period of activity (PV 1-2, 920 ± 20; HS 2-1, 960 ± 80; HS 2-2, 960 ± 80).

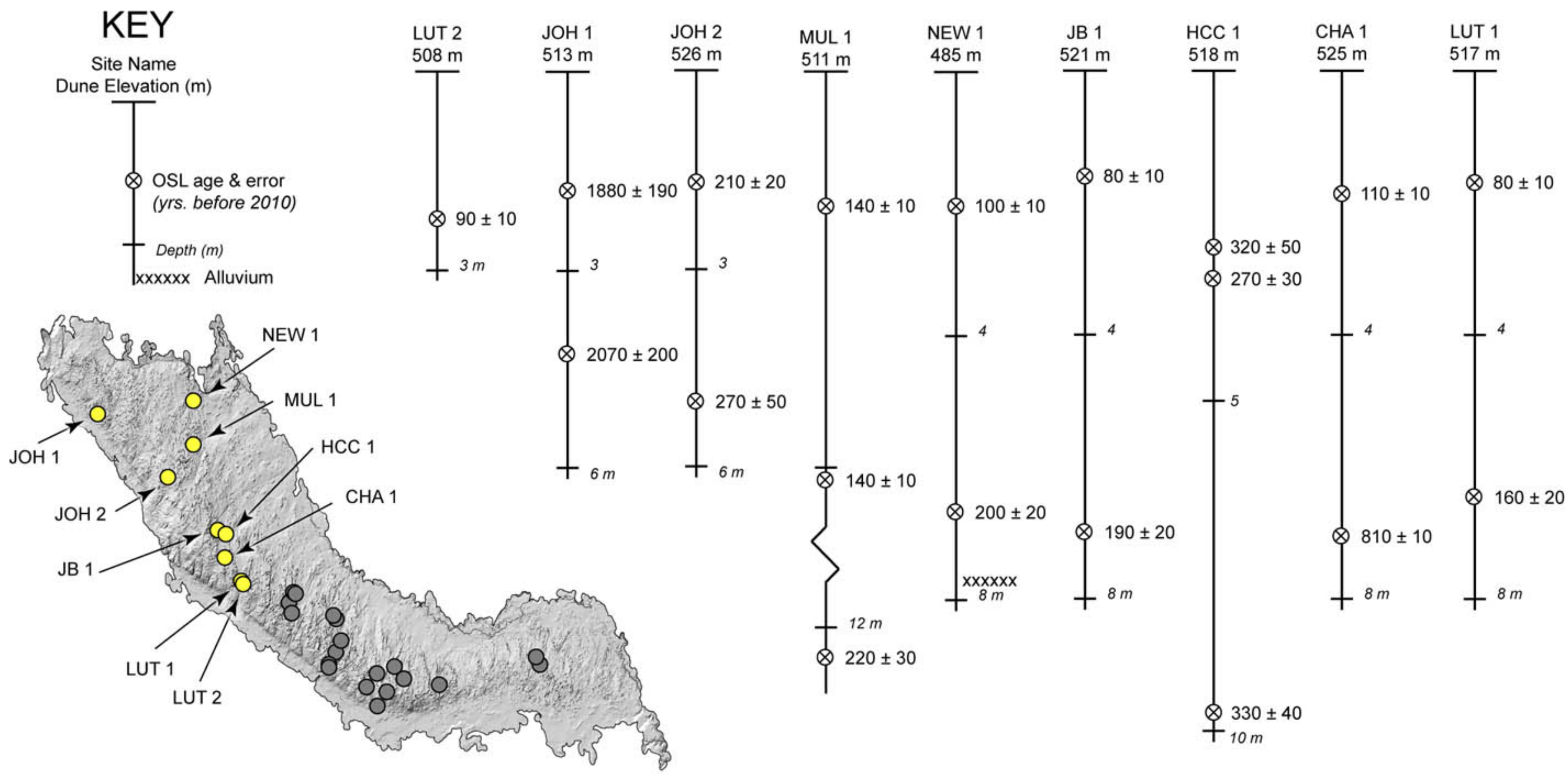

Figure 3.4. Depth relationships of OSL samples collected from the northwest section of the Hutchinson dunes. OSL ages are reported in years before 2010 and shown with 1σ errors. Elevations of auger sites are given in meters above sea level.

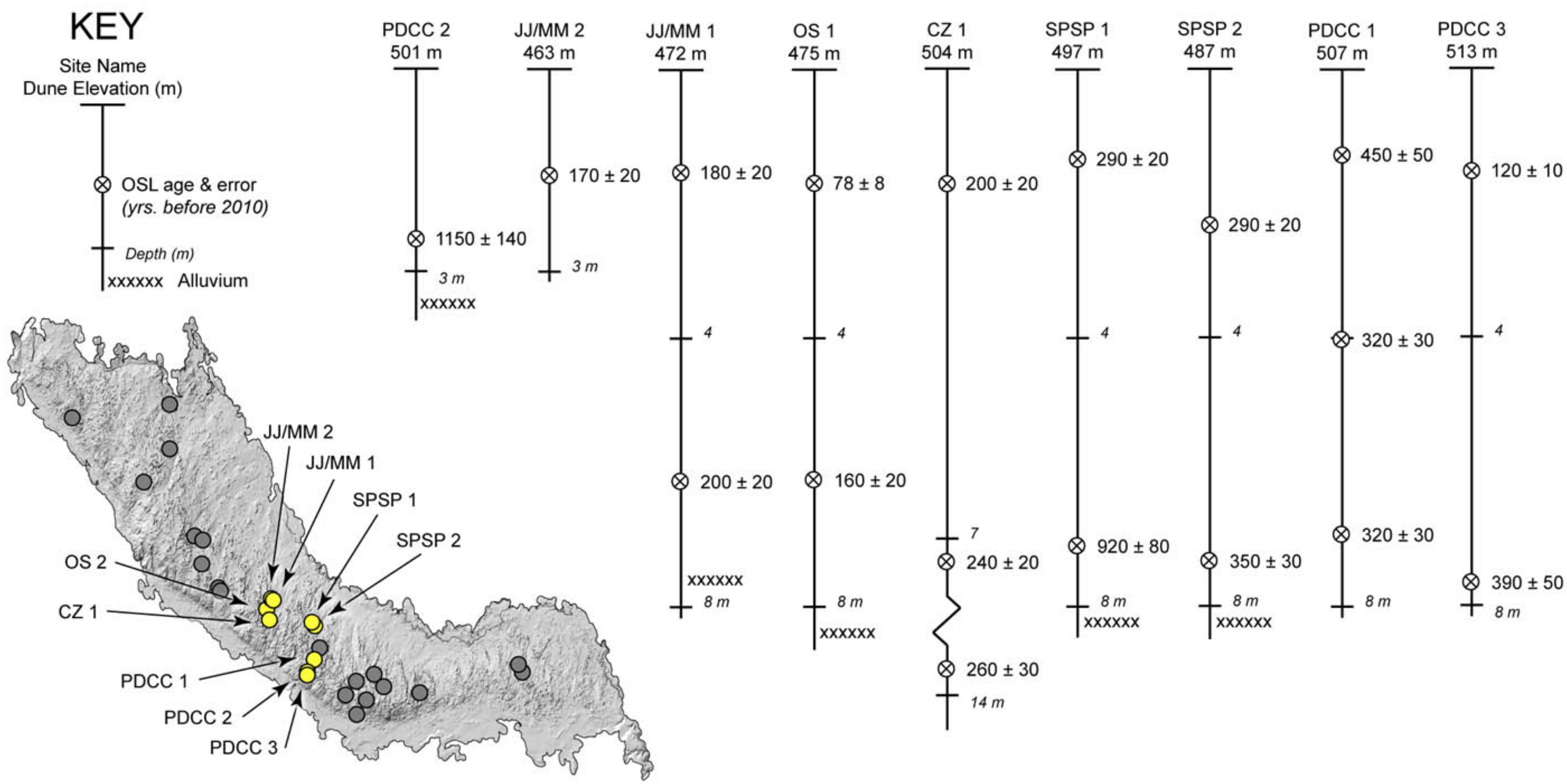

Figure 3.5. Depth relationships of OSL samples collected from the central section of the Hutchinson dunes. OSL ages are reported in years before 2010 and shown with 1σ errors. Elevations of auger sites are given in meters above sea level.

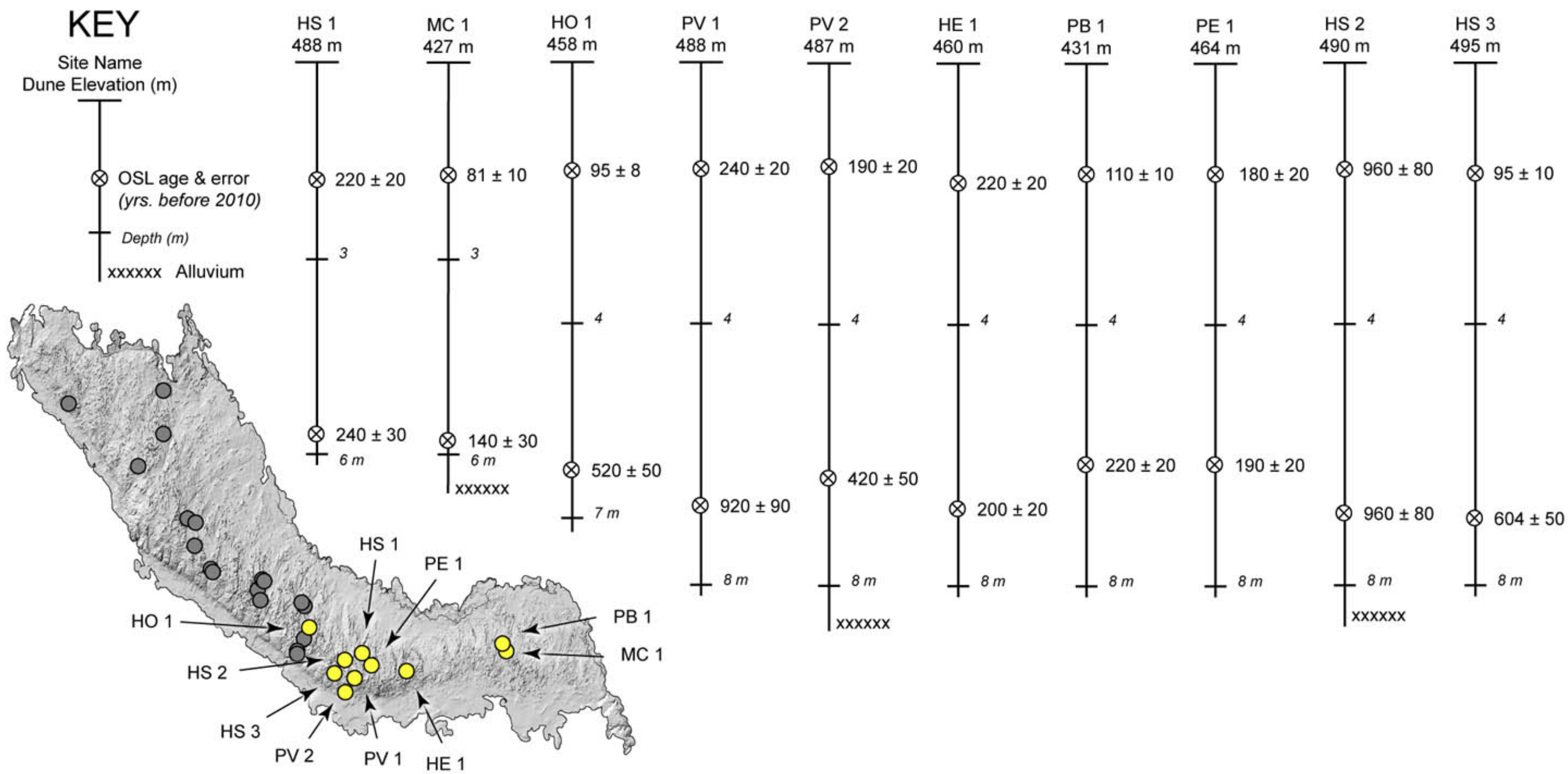

Figure 3.6. Depth relationships of OSL samples collected from the southern section of the Hutchinson dunes. OSL ages are reported in years before 2010 and shown with 1σ errors. Elevations of auger sites are given in meters above sea level.

3.5.2 Marginal dune field sites

3.5.2.1. Cullop Site

The Cullop Site (CUL) is located within the western arm of a large (~2 km2), southward-oriented parabolic dune located on an alluvial surface about 5 km west of the main dune field (Figs. 3.2, 3.7A). The site was selected because it and two accompanying parabolic dunes have a surface morphology unlike any other in the study area. Specifically, these are the only dunes with a distinct morphology indicating formation under a northerly wind regime. A profile, created in a ~2 m exposure (Fig. 3.7B), consisted of aeolian sediments that were fine, dark, and reactive (10% HCl), in contrast to those in the main dune field. Visible stratigraphy noted in the profile dipped between 13º and 16º to the west, and a krotovina crosscut the profile at a dip of 26º to the east. Based on the morphology of the dune sampled, the stratigraphy at this site is interpreted as the sideslope of a parabolic-dune wing. Visible lamella and thin packages of coarse sediment in the profile followed the dipping stratigraphy. An OSL sample (CUL 1-1) from the base of the profile (1.8 m) yielded an age of 2050 ± 190 years ago. Bucket auguring used to extend the profile to ~5.5 m revealed no detectable sedimentary changes. An additional OSL sample (CUL 1-2) collected using the bucket auger at 5.3 m yielded an age of 2080 ± 200 years ago.

3.5.2.2. Alluvial Sites (Young, Showalter, and Prairie Dunes Country Club 3)

The Young site (YG) is a ~6 m-deep sand quarry ~40 km south of the Hutchinson dunes (Figs. 3.2; 3.8). Although this site is the most distal from the dune field, it does expose alluvial stratigraphy similar to that in the main dune field. Coarse sand and gravel dominate the quarry sediment and are capped by a dark, fine-grain, organic- and carbonate-rich zone. Two OSL samples were collected from the alluvium below this zone, one on the northern quarry face at 2.1 m and another on the western quarry face at 1.7 m. Ages of these samples exceeded the limits of OSL dating, but minimum ages were

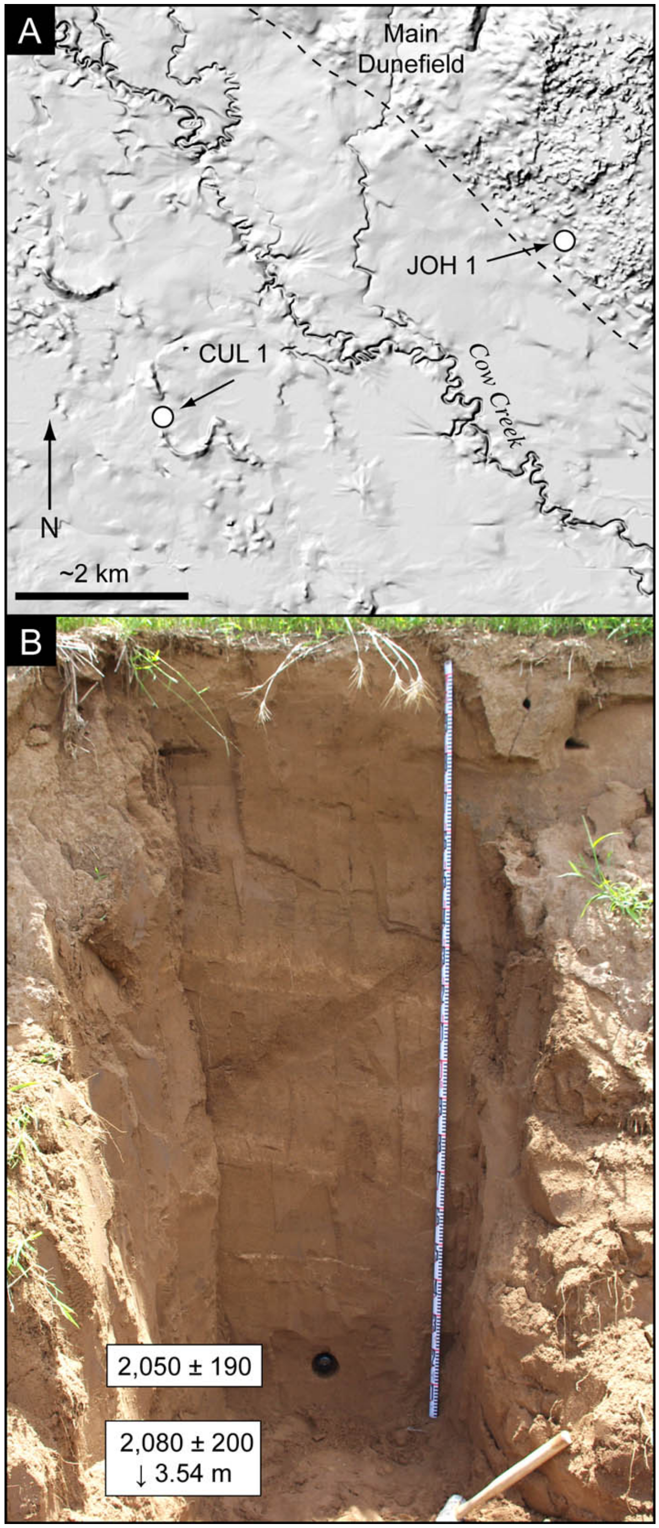

Figure 3.7. Location and stratigraphy of the Cullop 1 site (CUL 1). A) Hillshade DEM showing three south-trending parabolic dunes, the location of the Cullop 1 and Johnson 1sites. B): Cullop 1 site profile showing dune stratigraphy and optical sample still within the profile face. A small-mammal burrow can be seen crosscutting the dune stratigraphy. Zones of light-colored sediment are small lenses of coarse-grain sand.

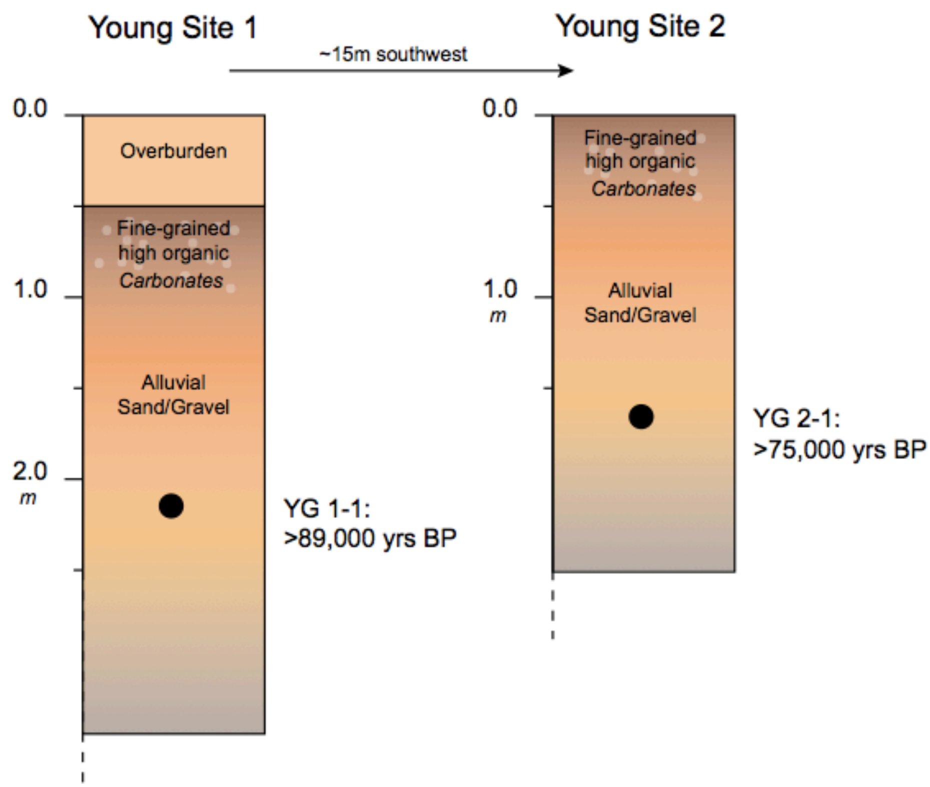

Figure 3.8. Stratigraphic profiles of the Young sites.

calculated for them: sample YG 1-1 was deposited prior to ~89,000 years ago, and YG 1-2 was deposited prior to ~75,000 years ago.

The Showalter site (SH) is located on southern edge of the Arkansas River valley ~10 km south of the dune field (Figs. 3.2; 3.9) (see supplemental file 3 for stratigraphic column). Alluvial stratigraphy of this site is similar to that of the Young Site in that it consists of coarse alluvial sand overlain by a dark, fine-grained, organic-rich deposit interpreted as a thin, pedogenically influenced loess deposit. In general, however, the alluvium at the Showalter site was not as coarse as that at the Young site. Two OSL samples were taken within the alluvium at 1 m and 2.5 m. Like those of the Young site, these samples were too old to date with OSL, but minimum age estimates were calculated for them, which indicated that the alluvium at the Showalter site was deposited prior to

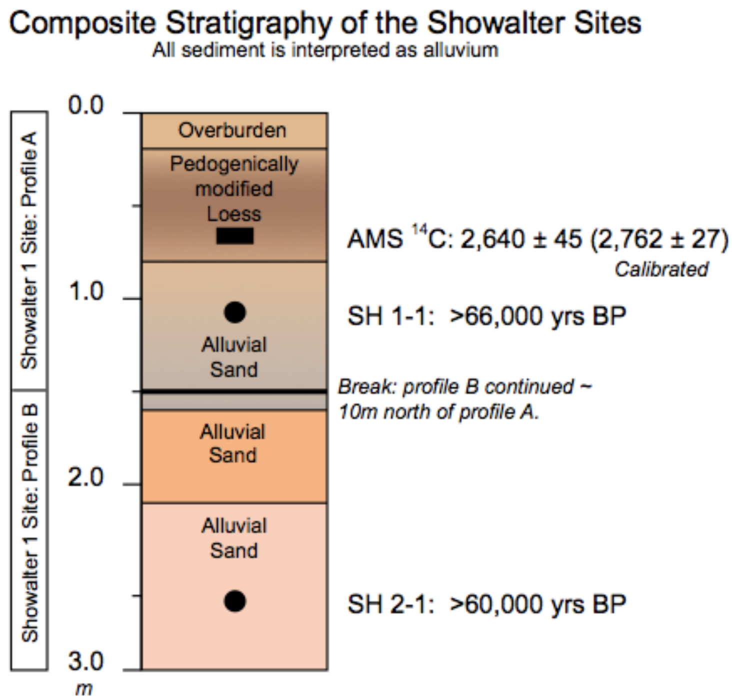

Figure 3.9. Composite stratigraphy of the Showalter sites.

~66,000–60,000 years ago (SH 1-1, SH 2-1). In addition to the two OSL ages, a radiocarbon sample collected at 50 cm in the loess yielded an age of 2,762 ± 27 calibrated years before present (2,640 ± 45 ^{14}C yrs BP).

Alluvial sediments, similar to those documented at the Young (YG) and Showalter (SH) sites, were also detected with a bucket auger at the Prairie Dunes Country Club 4 Site (PDCC 4), an interdune site adjacent to the PDCC 3 Site. At the PDCC 4 site, an upper alluvial unit consisting of fine-grained, gleyed sediment occurred at 2.4 m and was underlain by reduced alluvial sand to a depth of ~4.5 m where auguring ceased. These alluvial sediments were interpreted as floodplain deposits overlying alluvial sands. A minimum age of >61,000 years ago (PDCC 4-1) was estimated from a sample taken within the alluvium at 4.2 m, demonstrating its deposition prior to ~61,000 years ago. Sediments interpreted elsewhere as alluvium were identified below the Hutchinson dunes while bucket auguring (see Figs. 4–6), however no OSL samples were collected from these sediments.

3.5.2.3. Trostle Site

The Trostle site (TR) is an exposure of loess in a road cut located southwest of and ~10 m above the modern Arkansas River (Figs. 3.2; 3.10). The site consists of ~2.8 m of oxidized loess with abundant carbonate concretions. OSL was used to date a zone of concentrated carbonate at 1.8–2.2 m. A minimum age estimate indicated loess deposition prior to ~77,000 years ago (TR 1-1).

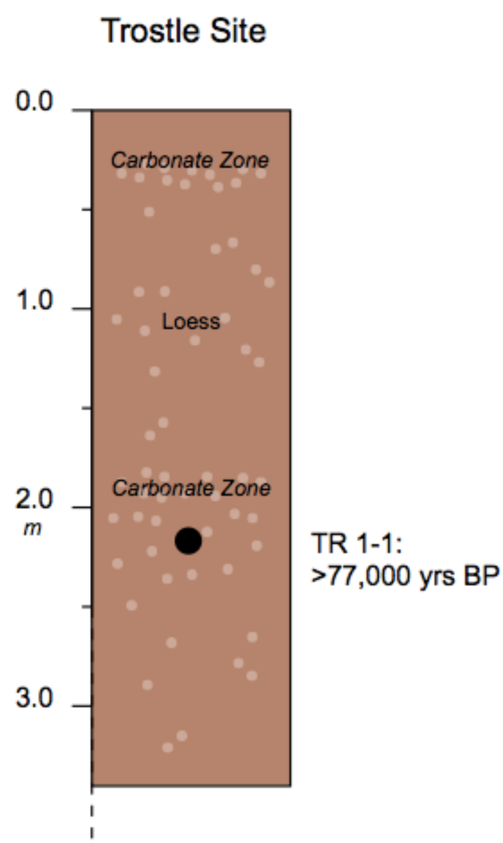

Figure 3.10. Stratigraphic profile of the Trostle site.

3.6. Discussion

3.6.1. OSL age inversions

All OSL ages are in stratigraphic order except for those at three sites: the Highlands Country Club site (HCC 1), Epps site (HE 1), and Prairie Dunes Country Club site 1 (PDCC 1). At HCC 1 (Fig. 3.4), an age 270 ± 30 (HCC 1-2) obtained from 3.2 m depth is overlain by an older age of 320 ± 50 (HCC 1-1) at 2.7 m. A similar case occurs at the Epps site (Fig. 3.6), where an age of 220 ± 20 (HE 1-1) at 1.98 m overlies an age of 200 ± 20 (HE 1-2) at 6.9 m. Both sets of ages fall within 1–2 σ of each other, and, therefore, no statistical difference exists between the pair of ages from each of the two sites. At the PDCC 1 site (Fig. 3.5), an age of 450 ± 50 (PDCC 1-1), sampled at a depth of 1.3 m, overlies two ages at 4 m and 7 m; both of these latter samples dated to 320 ± 30 (PDCC 1-2, 1-3). Considering that the ages at 4 m and 7 m are identical, the near-surface (1.3 m) age is most likely erroneous.

3.6.2. Hutchinson dunes chronology

The suite of accepted ages (n=65) documents three larger periods of aeolian activity between ~2100–1800 years ago, ~1000–900 years ago, and after ~600 years ago, as well as deposition of Pleistocene alluvium and loess prior to ~90,000–60,000 years ago and ~77,000 years ago, respectively. The high concentration of dune ages within the last 600 years, relative to those in the other age clusters, suggests that recent aeolian activity was intense and widespread. Our chronology also provides an estimate on the size of migrating dunes at this time, which in some cases exceeded heights of 8–10 m (e.g., CZ 1, HCC 1, MUL 1). Considering that present-day dune forms are similar in size to those that migrated within the past 600 years, the majority of the dune field must have been active during this time, rather than simply isolated blowouts or localized accumulation of aeolian sediment. Additionally, aeolian activity in the Hutchinson dunes within the last 600 years, especially the dune activation between ~420–70 years ago may have been sufficiently widespread as to overprint much of the evidence for prior aeolian activity. This may include overprinting of eolian activity between ~1000–900 years ago and ~2100–1800 years ago, and possibly even older periods of dune activation. Despite this potential bias, the Hutchinson dunes still contain evidence of late-Holocene dune activation, which correlate with other regional dune fields and proxies.

Five samples from an alluvial terrace ~16–20 m above the modern Arkansas River produced ages indicating deposition occurred prior to ~90,000–60,000 years ago. These ages are older than those of terraces upstream underlying the Great Bend Sand Prairie and Arkansas River dunes, which were deposited ~16,000 years ago (Arbogast 1996; Forman et al., 2008). Unlike the terrace underlying the Hutchinson dunes, those underlying the Great Bend Sand Prairie and Arkansas River dunes are only 3–5 m and 4–6 m above the modern Arkansas River, respectively (Arbogast, 1996; Arbogast and Johnson, 1998; Forman et al., 2008). Our OSL age estimates for the alluvial fills that underlie the Hutchinson dunes area are also supported by ages from loess deposition at the Trostle site, which suggests that underlying alluvial surface was abandoned prior to ~77,000 years ago.

The earliest period of dune activity in the Hutchinson dunes is documented with four ages from two sites that cluster between ~2100–1800 years ago. These ages are not documented throughout the dune field, but are geographically isolated in the northwestern corner. Two of these ages (CUL 1-1, CUL 1-2) were obtained from the Cullop site, the large south-trending parabolic dune located on alluvial sediments of Cow Creek (Fig. 3.7). Because dune morphology at the CUL 1 site does not match the wind vectors required to form the Hutchinson dunes, activity between ~2100–1800 years ago does not likely represent the first episode of aeolian dune formation in the Hutchinson dunes area. The two additional ages documenting activity between ~2100–1800 years ago (JOH 1-1, JOH 1-2) were derived from a dune ridge at the periphery of the main dune field. In the Great Bend Sand Prairie, only 50 km southwest of CUL 1, Arbogast (1996)

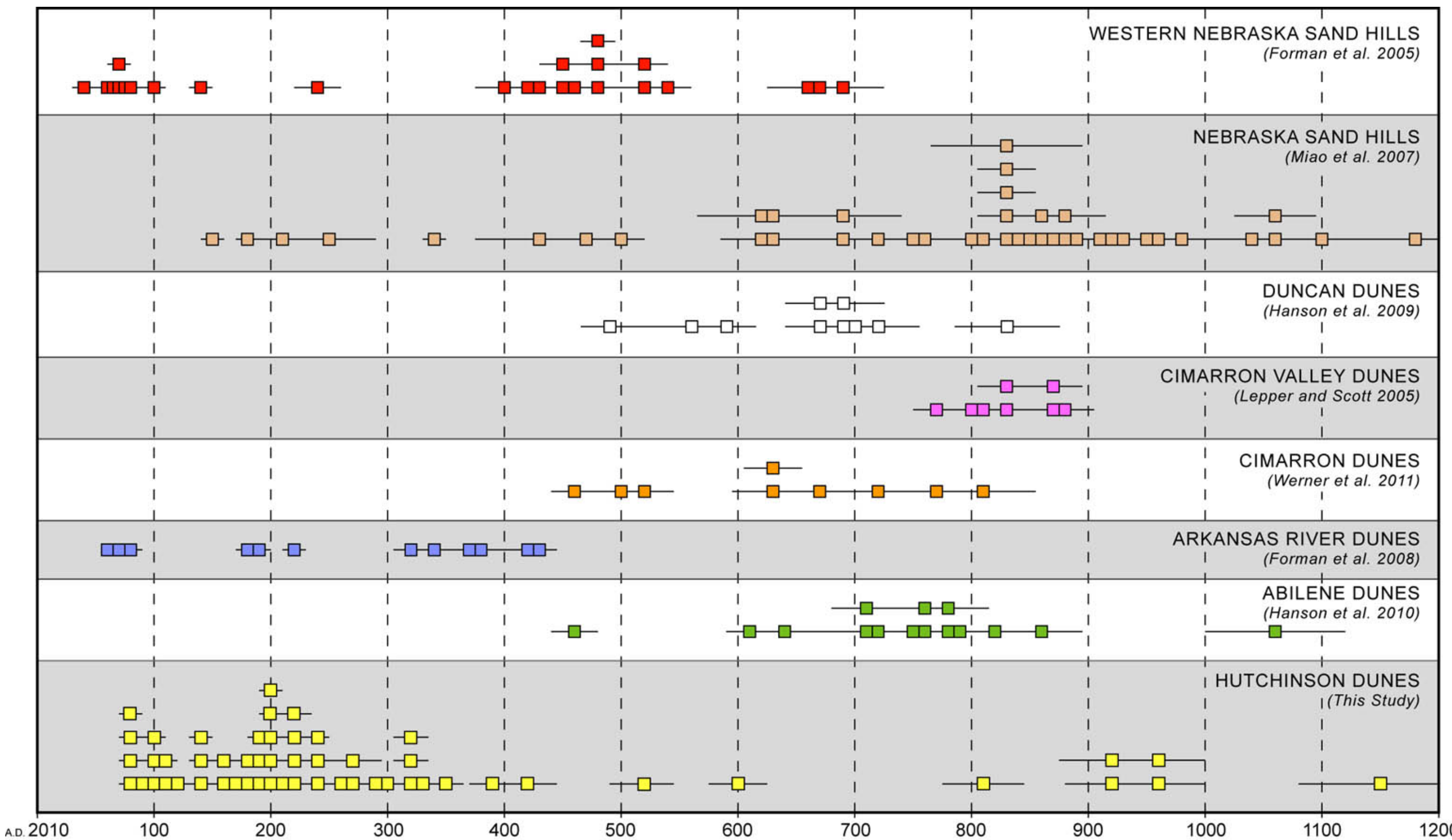

Figure 3.11. Asymmetrical point plots of OSL ages from dunes in the central Great Plains, including data from this study. Ages are presented in cal years before A.D. 2010.

and Arbogast and Johnson (1998), using radiocarbon ages from weakly developed buried soils, constrained dune activity within four parabolic dunes between ~2300 and ~1400 years ago.

While only a limited number of ages from the Great Bend Sand Prairie and the Hutchinson dunes support activity ~2100–1800 years ago, they may indicate a period of drier floodplain conditions during which alluvial or previously deposited aeolian sediments were reworked. Dune activity ~2100–1800 years ago may have occurred throughout the entire dune field; however, the younger episodes of aeolian activity may have erased most of this record except in specific localities (e.g., CUL 1, JOH 1). These sites were most likely spared during younger episodes of dune activity due to their proximity to Cow Creek (Fig. 3.7), which may have provided a higher water table sufficient to stabilize the adjacent landscape when the rest of the dune field was active ~1000–900 years ago. This increased stability led to greater soil development, which in turn aided in keeping these dunes stable during the most recent episodes of aeolian activity within the last ~600 years. A similar scenario was documented by Werner et al. (2011) where older dunes with better-developed soils (i.e., a greater abundance of fine particles) could retain moisture and remain stable during drought conditions, whereas younger dune forms with less developed soils could not.

A single age of ~1100 years ago was obtained from the Hutchinson dunes but does not cluster with any of the other ages. If correct, this age may represent a period during which isolated dune activity occurred, similar to the manner in which isolated blowouts form in other Great Plains dune fields today. Activation could have occurred in the Hutchinson dunes after ~1800 years ago and ended before ~1000 years ago, because similar timing of aeolian activity was recognized in the Great Bend Sand Prairie at this time (Arbogast, 1996; Arbogast and Johnson, 1998). The current age data are too limited, however, to document this distinctive period of activity.

The second period of aeolian activity (~1000–900 years ago) is indicated by four ages scattered throughout the dune field. With the exception of one age (HS 2-1), all were obtained from samples at depth, directly above the underlying alluvial surface, although they may not represent initial formation of the dunes. These ages may represent a reactivation event that overprinted most of the earlier dune activity ~2100–1800 years ago, or earlier. Widespread aeolian activity is documented ~960 years ago at HS 2, where two identical ages (HS 2-1, HS 2-2) are separated by ~5 m of aeolian sand, suggesting the rapid accumulation of sand or migration of an entire dune form at this time.

Activity ~1000–900 years ago correlates with a period of aeolian activity in the Great Bend Sand Prairie, which was bracketed by weakly developed soils dating to ~1000 and 700 years ago (Arbogast, 1996; Arbogast and Johnson, 1998). A lone age of 810 ± 70 years ago (CHA 1-2) was collected from the CHA 1 site, but, this age is not considered to cluster with those between ~1000–900 years ago because no other ages of ~810 years ago were obtained from the dune field. This age is probably erroneous, though, it is still plausible that dunes were active in the Hutchinson dunes ~810 years ago given that activity was noted in the Great Bend Sand Prairie ~800 years ago (Arbogast 1996; Arbogast and Johnson, 1998).

The most recent period of aeolian activity in the Hutchinson dunes began ~600 years ago and became more widespread by ~420 years ago, eventually peaking at ~320 and ~200 years ago. These peaks appear to correspond with the movement of significant quantities of sand in the Hutchinson dunes. For example, ~9 m of sand accumulated at ~330 years ago at the HCC 1 site, ~13 m of sand between ~260–200 years ago at the CZ 1 site, and ~12 m of sand at ~220–140 years ago at the MUL 1 site (Figs. 4, 5).

Dune activity continued into historic times, perhaps in response to 19th century droughts, such as the 1910s and 1930s. Evidence of historic dune activity was found in documents dating to the early settlement of Hutchinson, Kansas. These documents, from the mid and late 19th century, indicate that the Hutchinson dunes were fully activated in the 1870s but had stabilized at some locations by the early 1900s (e.g., Cole, 1918; Bradshaw, 1957). Dune activity during the 1930's Dust Bowl is also well documented by historical accounts and photography.

Dune activation in the past 700 years correlates well with records from the Great Bend Sand Prairie by Arbogast (1996) and Arbogast and Johnson (1998), where they reported dune activity occurring after brief periods of stability dating to ~700, ~500, and ~300 years ago. The brief periods of stability in the Great Bend Sand Prairie were indicated by thin (~10–20 cm) buried soils (Ab Horizons). Unlike the Great Bend Sand Prairie, however, no such buried soils were found in the Hutchinson dunes. While our sampling strategy included only a fraction of the dunes in the dune field, it is unlikely that any soils formed as the result of widespread stability were missed. Rather, any stability during the last 600 years may have been too short-lived to foster visible accumulations of organic matter, or at least none that survived ensuing episodes of aeolian activity.

Most evidence points suggests that identified periods of dune activity were the result of extended reductions in moisture (i.e., drought), which resulted in the desiccation of vegetation and subsequent activation of dune field. While other factors such as a rapid influx of sediment could potentially cause dune activity (e.g., Muhs et al., 1996; Hanson et al., 2009), all evidence in the Hutchinson dunes suggest this is not the case. For example, no well-developed dunes are found on the floodplain between the Hutchinson dunes and the modern Arkansas River, a distance of ~10 km. Additionally, there is no correlation between ages of dune activation and distance from the Arkansas River. If dune activity were driven by changes in sediment supply, one would expect to see younger dunes closer to the river.

3.6.3. Regional comparisons of late-Holocene dune activation

The activation chronology of the Hutchinson dunes presents a new, high-resolution chronology of dune activity in the Great Plains and defines periods of aeolian activity that have been observed in other Great Plains dune fields. One period of activity that appears in both the Hutchinson dunes and neighboring Great Bend Sand Prairie is that documented between ~2100 and 1800 years ago, though, this activity is absent from many other Great Plains dune fields. For example, dune activity occurred prior to ~2300 years ago in the Nebraska Sand Hills with a peak in activity ~2500 years ago (Goble et al. 2004; Miao et al., 2007a), and the Fort Morgan dunes of Colorado were active ~2300 years ago (Clarke and Rendell, 2003). Dune activity between ~2100 and 1800 years ago is also absent from dune fields in Oklahoma (Lepper and Scott, 2005; Werner et al., 2011). Limited activity was noted in dune fields of Wyoming between ~2100 and 1800 years ago (e.g., Mayer and Mahan, 2004; Halfen et al., 2010), but this activity may not have been climatically linked to a drought covering the entire Great Plains, because the Nebraska Sand Hills and numerous other dune fields separating Kansas and Wyoming did not record the same activity. Nevertheless, formation of well-developed, south-trending parabolic dunes at this time (e.g., CUL 1 site) clearly indicates that activity was present in at least the Hutchinson dunes and neighboring Great Bend Sand Prairie.

Albeit somewhat earlier than many dune fields, the second period of dune activity in the Hutchinson dunes (~1000–900 years ago) is coincident with widespread activity recognized within the Great Plains, including the Nebraska Sand Hills, active ~1000–700 years ago (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007a) (Fig. 3.11), the Fort Morgan dunes, active ~1,000 and ~800 years ago (Clarke and Rendell, 2003); and the Muleshoe dunes of the Southern High Plains, active after ~1300 years ago up until ~800 years ago (Holliday, 2001). The Cimarron Valley dunes show activity ~900–760 years ago (Lepper and Scott, 2005) and the Cimarron Bend dunes ~800–500 years ago (Werner et al., 2011) (Fig. 3.8). In addition, dune activity was identified in the

Duncan dunes between ~800 and 500 years ago and in the Abilene dunes between ~900 and 500 years (Hanson et al., 2009; 2010) (Fig. 3.11). Both these latter dune fields are eastern Great Plains dune fields, and their activity, together with that documented in the Hutchinson dunes, suggest that dune fields across the Great Plains were active at this time.

Regional dune activation ~1000–900 years ago is probably related to climate conditions associated with the MCA, as was suggested to be the case in the Nebraska Sand Hills (Miao et al., 2007a), Duncan dunes (Hanson et al., 2009), and Abilene dunes (Hanson et al., 2010). Several continental-scale drought reconstructions indicate megadroughts occurred in the Great Plains and surrounding areas during the MCA (Booth et al., 2006; Feng et al., 2008; Cook et al., 2009). Though the exact climatic cause of these droughts is still not fully understood, they have been attributed to increased La Niña conditions in the tropical Pacific Ocean (e.g., Feng et al., 2008; Cook et al., 2009) and possibly even warm sea-surface temperatures in the North Atlantic Ocean (Feng et al., 2008).

Unlike many Great Plains dune fields, the Hutchinson dunes show little evidence for activation between ~800 to 600 years ago. Whether the lack of ages at this time represents stability or a sampling/preservation bias is unknown. Given the timing of dune movement identified in the Hutchinson dunes, a preservation bias against older activation events clearly exits, including the period of activity between 800 and 600 years ago. A bias could also exist because every dune was not sampled within the dune field, or a potentially unrecognized problem with the OSL dating may also account for a lack of ages at this time. It is still reasonable, however, that the Hutchinson dunes may have stabilized by this time considering that weakly developed soils in the proximal Great Bend Sand Prairie formed ~700 years ago (Arbogast 1996; Arbogast and Johnson 1998). If the Hutchinson dunes were stable at this time, any evidence of their stability was erased by later episodes of dune activity.

Many Great Plains dune fields also express dune activity throughout the past ~600 years, though the timing of this activity varies somewhat across the region. For example, Forman et al. (2005) documented four periods of aeolian activity during the past 600 years in far western areas of the Nebraska Sand Hills, ~470, ~240, ~140, and 70 years ago, yet only a handful of similar ages have been obtained from the rest of the Sand Hills (e.g., Goble et al., 2004; Miao et al., 2007a). Records derived from other dune fields, especially those of the western Great Plains, show activity during the past 600 years as well. Muhs et al. (1997b) identified activity during this time in the Wray dunes (Fig. 3.1), which was further supported by Clarke and Rendell (2003), who reported the last major period of activity in the Fort Morgan dunes beginning at ~600 years ago and lasting until ~370 years ago. Dune activity was also reported in the Arkansas River dunes ~430, 380–320, 180, and 70 years ago (Forman et al., 2008) (Fig. 3.11), and dune activity occurred after ~600 years ago in the Cimarron Bend dunes (Werner et al., 2011) (Fig. 3.11) as well, but this activity ceased by ~450 years ago.

Significant aeolian activity also occurred in the Southern High Plains within the last ~700 years. For example, the Muleshoe dunes were active after ~700 and ~500 years ago, and the Seminole sandsheet was active between ~400 and ~300 years ago (Holliday, 2001). The Muleshoe dunes and Seminole sandsheet, as well as the Lea-Yoakum and Andrews dunes of Texas, were all active within the last 200 years (Holliday, 2001).

The geographical distribution of dune fields with activity after ~600 years ago prompted Hanson et al. (2010) to conclude that most dune activity in the Great Plains at this time was restricted to areas west of the 500 mm isohyet (Fig. 3.1). Data from the Hutchinson dunes, located east of the 700 mm isohyet, indicate that this is not the case for all locations in the Great Plains. Dune activity during the last 600 years was not restricted to western Great Plains dune fields, but also to dune fields in the southern High Plains. This pattern of drought may be similar to that observed during the extensive droughts of the 1930s and 1950s. During these droughts, the Panhandle of Oklahoma and southwestern Kansas experienced widespread drought, whereas areas of the northern and eastern Great Plains did not (e.g., Schubert et al., 2004; Seager et al., 2008; Cook et al., 2009). Further evidence that droughts impacting the Great Plains within the last 600 years were more geographically isolated than those of that occurred during the MCA has been documented in other Great Plains proxies (e.g., Fritz et al., 1994; Laird et al., 1996; Fritz et al., 2000).

Hutchinson dune activity during the past 600 years, especially increased activity after ~420 years ago, correlates well with the coolest periods of the LIA (cf. Mann et al., 2009). Widespread, continental megadroughts of the LIA are not as well recognized as those during the MCA. Nevertheless, Cook et al. (2009) concluded that North America remained under drought-prone climates following the MCA well into the LIA, and, despite drought-prone climate, many dune fields of the Great Plains did stabilize at this time. Several tree-ring reconstructions also document drought in the mid-continental North American during the past 600 years (e.g., Stahle et al., 2000; Herweijer et al., 2006). Fritz et al. (1994) documented drought in the northern Great Plains during the LIA, but this record did not agree with Laird et al. (1996), who reconstructed mesic conditions during the same time. Fritz et al. (2000) later argued that drought occurred during the LIA, but that decreases in precipitation during the LIA were not anomalous compared to the longer-term hydrological patterns of the Great Plains. It is clear from these records that drought, while not as widespread as during the MCA, was present in the Great Plains during the LIA. Dune activation ages from the Hutchinson dunes has allowed for re-evaluated geographical patterns of LIA megadrought activity, and, based on these ages, LIA droughts were restricted more to the southern and western Great Plains.

3.7. Conclusions

Numerous OSL ages provide a reliable chronology of dune activation for the Hutchinson dunes, resulting in the identification of three significant periods of dune activity ~2100–1800 years ago, ~1000–900 years ago, and after ~600 years ago, especially within the past 420–70 years. Regional correlation between dune activity in the Hutchinson dunes and that of other Great Plains dune fields is limited between ~2100–1800 years ago, however dune activity ~1000–900 years ago and that within the last 600 years correlates well. As previous investigations have hypothesized, dune activity in the Great Plains ~1000 years ago appears to correlate with significant climate change associated with the MCA, though the Hutchinson dunes appear to stabilize earlier than many other Great Plains dune fields at this time. Nevertheless, the geographical location of dune fields with activity after ~1000 years ago suggests that megadroughts impacting the region during the MCA were widespread and impacted most of the Great Plains. Activity in the Hutchinson dunes during the past 600 years does not correlate well with that of other northern and eastern Great Plains dune fields. It does correlate, however, with activity reported for western Nebraska and Colorado, Oklahoma, the Arkansas River valley of Kansas and the Southern High Plains, suggesting that widespread droughts also impacted the Great Plains throughout the LIA and into historic times. Notably, droughts during the LIA were less extensive and limited more to the southern and western Great Plains. Despite being less extensive, droughts at this time were significant in that the Hutchinson dunes were active with migrating dune forms exceeding 8–10 m in height.

Chapter 4

A LATE-QUATERNARY RECORD OF AEOLIAN ACTIVITY FROM THE ARKANSAS RIVER DUNES

4.1. Introduction

The North American Great Plains is a vital, global agro-economic region that supplies more than half of the world's wheat production, 40% of which is exported from the United State and Canada throughout the globe (Wishart, 2011). Future changes to the region's climate, which include projected increases in temperatures by as much as 4ºC by A.D. 2100 and more frequent and severe drought, will have a dramatic impact on the sustainability of the Great Plains landscape (Brunsell et al., 2010; GCC, 2012). Key to mitigating the effects of future Great Plains droughts is understanding the impacts these events have had on the region in the past.

Extreme droughts are not phenomena new to the Great Plains, and, within the past century, the region has experienced repeated droughts (i.e., 2000s, 1980s, 1950s and 1930s) (Woodhouse and Overpeck, 1998; Cook et al., 2009). Droughts were also commonplace in the Great Plains prior to the 20th century, and, in some cases, these prehistoric droughts were significantly more intense and more geographically extensive than any drought that impacted the Great Plains during historical times (Woodhouse and Overpeck; 1998; Cook et al, 2009). The term "megadrought" has been adopted by researchers to describe these prehistoric droughts, which are defined as droughts of greater intensity and spatial coverage than the 1930's Dust Bowl (Woodhouse and Overpeck, 1998; Forman et al., 2005).

The propensity for prehistoric Great Plains megadroughts has been widely documented in many paleoclimatic records, including tree-rings series (e.g., Grissino-Mayer, 1996; Stahle et al., 2000; Cook et al., 2004; Cook et al., 2007; Stahle et al., 2007), stratigraphic analysis of fossil pollen (e.g., Fredlund, 1995; Dean, 1997; Baker et al., 1998; Nordt et al., 2008; Baker et al., 2009), and diatom-inferred lake salinity records (e.g., Laird et al., 1996; , Fritz et al., 2000; Grimm et al., 2011; Hobbs et al., 2011; Schmieder et al., 2011). Though these records provide a great deal of information on the paleoclimatic history of the Great Plains, including information on the timing and expansiveness of prehistoric droughts, they are often limited by their spatial and temporal coverage (Woodhouse and Overpeck, 1998; Stahle et al., 2007). For example, while tree-ring reconstructions provide excellent annual climatic data, these records are mostly absent from the central Great Plains (e.g., Kansas), especially those that extend beyond the last 1000 years (e.g., Woodhouse and Overpeck, 1998; Cook et al., 2007). Similarly, pollen- and diatom-reconstructed climate records may span several millennia, yet their spatial coverage is limited (Larid et al., 1996; Dean, 1997; Laird et al., 1998; Fritz et al., 2000).

Great Plains aeolian dune fields alternately provide a unique proxy for studying the temporal and spatial patterns of prehistoric Great Plains megadroughts because 1) dune fields are ubiquitous features of the region; 2) dune fields, by their nature, activate in response to drought conditions; 3) dune activity is well preserved in the aeolian stratigraphic record; and 4) periods of aeolian activity are easily and accurately dated using optically stimulated luminescence (OSL) dating techniques. As a result, chronologies of Great Plains dune activity have provided much of that which is currently known about the timing and spatial patterns of prehistoric megadroughts (see review in Chapter 2 of this dissertation).

Despite our understanding of prehistoric Great Plains megadroughts, several components of their spatial and temporal patterns remain unresolved. For example, not all Great Plains dune fields record the same periods of prehistoric megadroughts, and, in some instances, dune field-derived drought chronologies within a similar area, or even multiple chronologies from the same dune field, document different periods of activity (e.g., Wolfe et al., 2007a; Forman et al., 2008; Wolfe and Hugenholtz, 2009; Halfen et al., 2010; Werner et al., 2011). Problems with correlating dune field activity may exist within the age data itself (Halfen et al., 2010), but may also be the result of other factors not related directly to drought, such as soil-geomorphic system feedback or sediment supply (e.g., Muhs et al., 1996; Hanson et al., 2009; Werner et al., 2011; Halfen et al., 2012). Nevertheless, dune field chronologies are useful and reliable proxies for documenting prehistoric megadroughts (Hanson et al., 2009; 2010; Werner et al., 2011; Halfen et al., 2012).

The goals of this study, therefore, are to 1) use OSL and accelerator mass spectrometry (AMS) radiocarbon (^{14}C) ages to produce a chronology of dune field activity from the Arkansas River dunes (ARD) in west-central Kansas (Fig. 4.1), which can be used to infer timing of prehistoric megadroughts, and 2) assess the degree of correlation between documented periods of drought in the ARD and other regional dune fields. The location of the ARD within the central Great Plains makes its record of prehistoric megadroughts an important proxy for evaluating the links between the northern and southern Great Plains, which may help to correlate drought records across the region. Additionally, the proximity of the dune field to the Arkansas River, a large, alpine-sourced, graded stream, provides a unique opportunity to evaluate the relationship between dune field activity and the fluvial and prehistoric glacial record.

4.2. Study area and methods

4.2.1. Arkansas River dunes

The ARD are situated within the Arkansas River valley, south of the river extending east–west 220 km from Ford, Kansas (99.75º W), to Granada, Colorado (102.60º W) (Fig. 4.2). Though only 30 km at its widest point, the dune field covers an area in excess of 3800 km^2. Climate of ARD is unique in that it spans a strong east-west precipitation gradient (Harrington and Harman, 1991). Winds vary east-to-west as well,

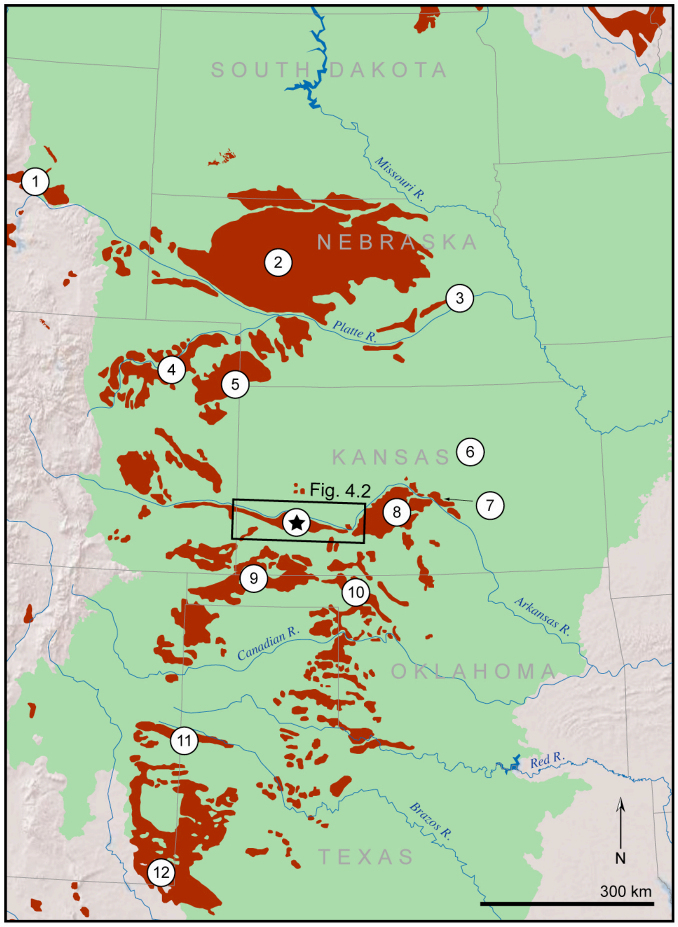

Figure 4.1. Dune fields of the central and southern Great Plains that have dune activation chronologies. Inset box is the approximate location of Figure 4.2. Dune Field key: (Star) Arkansas River Dunes (ARD)(this study); 1) Casper Dunes; 2) Nebraska Sand Hills; 3) Duncan Dunes; 4) Fort Morgan Dunes; 5) Wray Dunes; 6) Abilene Dunes; 7) Hutchinson Dunes; 8) Great Bend Sand Prairie; 9) Cimarron Bend Dunes; 10) Cimarron Valley Dunes; 11) Muleshoe Dunes; 12) Mescalero and Monahans Dunes.

with those in the east predominantly from the south and strongest during the summer, while winds in the western dune field have an equal summer-southerly and winter-northerly component (Schmeisser et al., 2010). The dune field is mostly stabilized, though active areas occur west of 100º W. Stabilized dunes are covered by short-grass, mixed prairie vegetation, which includes little bluestem (*Schizachyrium scoparium*), blue grama (*Bouteloua gracilis*), and sagebrush (*Artemisia)* (Küchler, 1974). East-west structural changes in vegetation are also observed, with more grasses and woody shrubs in the eastern dune field and a greater presence of yucca (soapweed: *Yucca glauca*) in the

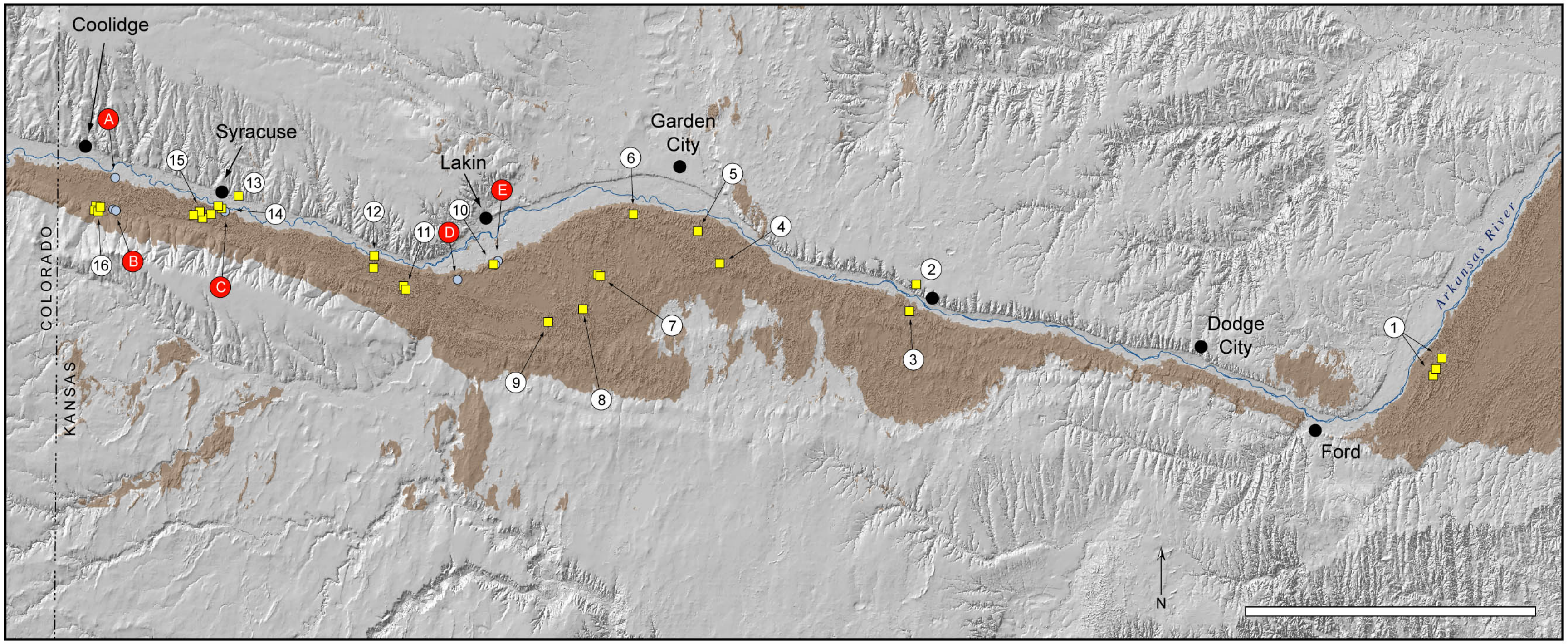

Figure 4.2. The ARD including sample site location from this study (numbers) and from Forman et al. (2008) (letters). The scale bar in the bottom right is ~50 km. Site key: 1) Pyle Ranch sites; 2) Ingalls Feedlot; 3) Ingalls Gravel Pit; 4) Brookover Ranch; 5) Garden City Sand Pit; 6) Gross Landfill; 7) J & O Cattle sites; 8) Price Ranch Site 1; 9) Price Ranch Site 2; 10) Grant County Quarry; 11) Land East sites; 12) P5 Ranch sites; 13) Syracuse Feedlot; 14) Tarbet Quarry sites; 15) Syracuse ATV Park sites; 16) Wharton Ranch sites. Forman et al. (2008) sites: A) site 4; B) sites 5 and 6; C) site 1; D) site 8; E) site 7 and 9.

far western dune field.

Dune relief is variable, but, in general, high relief dunes (10–20 m) are best expressed proximal to the Arkansas River, whereas lower-relief dunes and sand sheets that grade into upland loess are located away from the river. Though not supported with mineralogical evidence, Simonett (1960) hypothesized that the ARD formed as northerly winds moved sand-sized alluvium from Wisconsinan-aged alluvial terraces, a theory supported by Forman et al. (2008) and by geochemical evidence from the Great Bend Sand Prairie east of the ARD (Arbogast and Muhs, 2000) (Fig. 4.1).

A variety of complex dune morphologies, which resulted from subsequent periods of aeolian activity overprinting older generations of dunes (i.e., 1930s dune activity overprint prehistoric activity), and more common dune morphologies found throughout the dune field include complex parabolic dunes (Fig. 4.3A–C), which generally indicate dune migration towards the north-northeast; large transverse dunes, which formed under north-northwesterly winds (Fig. 4.3D–F); hummocky dome type dunes or nebkha dunes, whose morphology records little paleowind data (Fig. 4.3B–C); and large dune blowouts (Fig. 4.3G). Dune height averages ~10–12 m, though the tallest dunes exceed 20 m in relief above the contact with the underlying alluvial terrace, which itself ranges from ~3–8 m above the modern Arkansas River channel. Underlying dunes close to the river are Pleistocene-aged alluvial deposits (Simonett, 1960; Forman et al., 2008), and, at the southern edge of the dune field, dune sediment inter-finger with Pleistocene Peoria Loess and middle-Holocene loess deposits, likely the fine-grained, distal component of the ARD system (Simonett, 1960; Arbogast and Johnson, 1996; Olsen et al., 1997).

4.2.2. Field methods

Stratigraphy was described, and OSL and AMS ^{14}C samples were collected from 35 sites within the Arkansas River valley (Fig 4.2; Tables 4.1; 4.2). Sample sites were

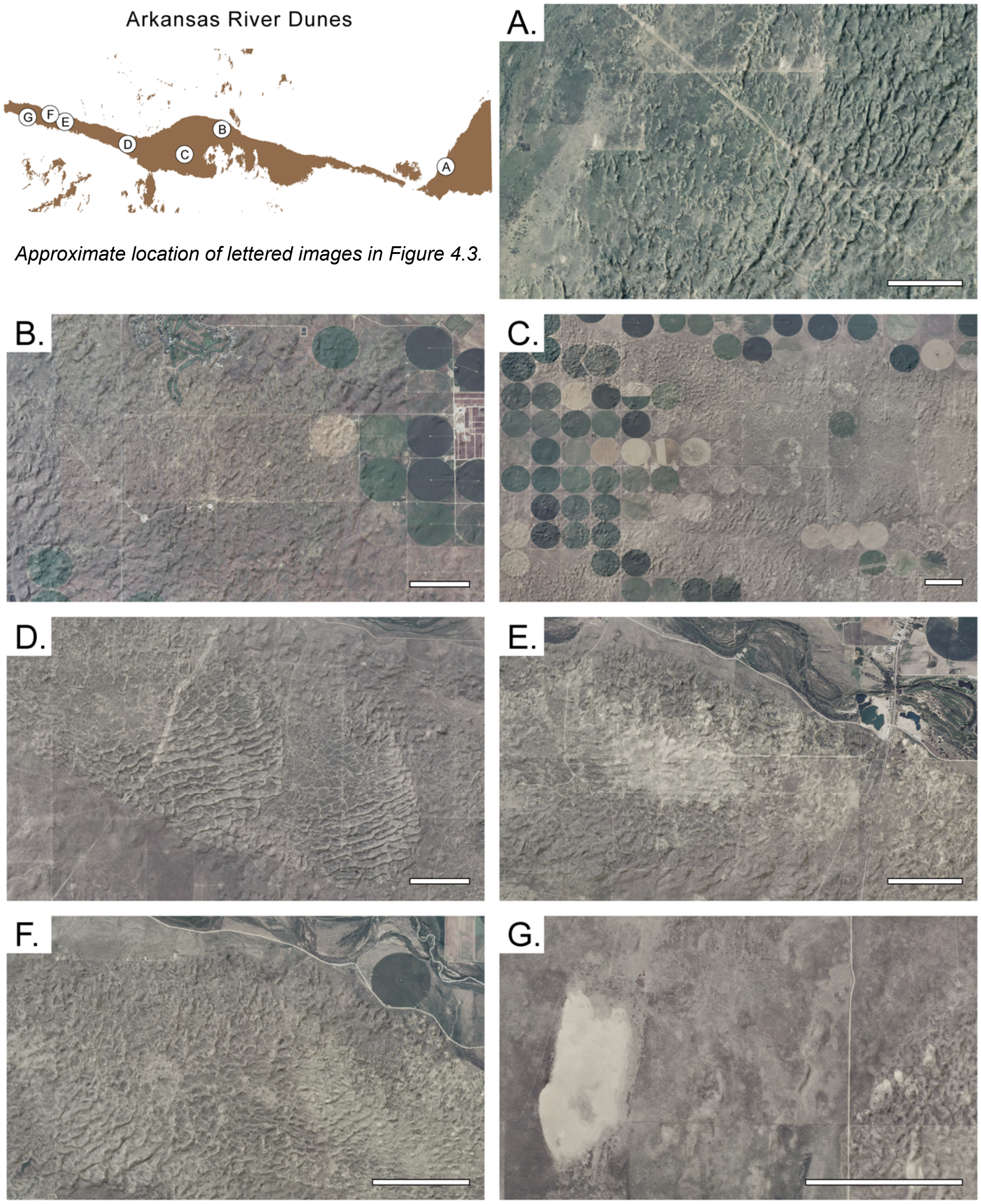

Figure 4.3. Dune morphology of the ARD. North is up in all figures. Scale bar in each image is approximately 1 km. A) Northeast-trending parabolic dunes of the Pyle Ranch; B) complex mixture of north-trending parabolic dunes and dome and nebkha dunes at the Brookover Ranch; C) dome dunes and parabolic dunes on the J & O Cattle and Price Ranch sites; D) Transverse dune ridges of the Land East sites—these southeastern-trending transverse ridges are overprinted with younger episodes of north-trending parabolic dunes; E) transverse dunes of the Syracuse ATV park—these dunes are the most active found in the dune field, principally due to ATV disturbance; F) southeastern-trending dunes, which have been overprinted by younger episodes of northward migrating parabolic dunes; G) a large blowout (~1 km^2) on the Wharton Ranch. Imagery from the National Agriculture Imagery Program (NAIP) (http://www.kansasgis.org/).

first identified using a combination of National Agriculture Imagery Program (NAIP) imagery, a low-altitude aerial survey, and ground-based field reconnaissance. Sample sites were selected with three primary considerations: sites should 1) record the greatest thickness of dune field and alluvial stratigraphy possible, 2) reflect the diversity of dune morphologies throughout the dune field, and 3) be within 1 km of an accessible road. Despite these considerations, the dune field was representatively sampled from natural blowouts, man-made exposures (e.g., gravel pits and landfills), and isolated dune crests, flanks, and swales. When possible, profiles were created within natural and man-made exposures so that dune and alluvial sediments could be described in detail (Fig. 4.4A, 4.4D–E). When creating a profile was not possible (e.g., dune crest, flanks, and swale sites), a hand auger was used to sample sediment (Fig. 4.4C–D). Though not ideal for describing stratigraphy, hand augers provide relevant information such as tactile changes in texture, color, and moisture. Regardless of the sampling method, a widely recognized procedure was used for identifying the sediments from which OSL and AMS ^{14}C samples would be collected and included maximizing sample collection at stratigraphic contacts and avoiding near-surface sediments, which may be pedoturbated. A careful procedure was followed when collecting OSL samples to avoid exposure of the sediment to light. Samples were collected directly in 15 cm long, 3 cm diameter, opaque steel tubes (electrical conduit), that were either hammered into a profile or inserted into full auger bucket (Fig. 4.4F–G). As the tube was removed, the sample inside was packed tightly, capped with black rubber caps and sealed such that no shifting could occur (Fig. 4.4H). Bulk sediment samples were collected immediately adjacent to the OSL sample for determining moisture content and geochemistry (OSL dose rate analysis).

4.2.3. OSL and AMS ^{14}C dating methods

OSL dating analysis was conducted at the University of Nebraska Luminescence and Geochronology Laboratory and the Kansas State Luminescence Laboratory.

Figure 4.4. Sampling strategy used in the ARD. AFH within each image is ~1.8 m tall. A) stepped profile within a dune blowout; B) horizontal bucket auguring within a blowout; C) vertical bucket auguring from the crest of a dune; D) sampling for OSL samples within a profile of an abandoned gravel quarry; E) stepped profile within a landfill; F–H) series of photos showing the collection procedure for OSL samples from a bucket auger: F) a clean, empty steel tube is inserted into a full bucket auger; G) view of full tube within the bucket; H) a full tube is extracted from the bucket and sealed with opaque caps so that no shifting of sediment can occur during transport from the field to the laboratory.

Although two laboratories were used, all OSL ages were derived following the same methodology, which is well established in the literature (e.g., Goble et al., 2004; Mason et al., 2004; Miao et al., 2007a; Hanson et al., 2009; 2010; Werner et al., 2011; Halfen et al., 2012). Despite a similar methodology, slight differences in the pretreatment protocol exist between laboratories. The pretreatment protocol, in general, serves to isolate quartz grains which contained datable luminescence signals.

Samples analyzed at the Kansas State Luminescence Laboratory (Table 4.1: KSU samples) were first dried and sieved to isolate the 212–250 μm grains, followed by a treatment of 1 N HCl to remove carbonate minerals and a 30% H_2O_2 treatment to remove organics. Samples were then floated in 2.7 g/cm^3 lithium metatungstate to separate heavy minerals from quartz and feldspar grains. After density seperation, samples were etched with 48% HF, and washed in 10% HCl before H_2O and $(CH_3)_2CO$ washes and drying. Preliminary OSL measurements indicated significant infrared signals, interpreted to be abundant feldspars grains. A 2.62 g/cm^3 density separation was carried out to further purify the quartz, followed by re-measurement.

A similar pretreatment procedure was used at the University of Nebraska Luminescence and Geochronology Laboratory (Table 4.1: UNL samples), though samples were sieved to isolate 90–150 μm grains and only underwent one density separation in 2.7 g/cm^3 sodium polytungstate to remove heavy minerals. The remaining sample was treated with 48% HF acid for ~75 minutes to remove feldspars and etch quartz grains, followed by a treatment in 47% HCl for ~30 min. Samples were then re-sieved to remove grains finer than 90 mm.

Equivalent dose (D_e) values were determined in both labs using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000, Murray and Wintle, 2003). OSL dating analyses were carried out on Daybreak and Risø TL/OSL readers. Five regenerative doses were used, including a zero dose and a repeated initial dose. Individual aliquots were rejected if their recycling ratios were > ± 10%, or, in some cases, if they had measurable signals during exposure to infrared diodes. Aliquots were also rejected if their equivalent dose (D_e) values were >4σ from the mean D_e value. Final age estimates were calculated using the mean D_e values from all accepted aliquots. Dose rate estimates were based on elemental concentrations of bulk sediment taken immediately adjacent to the OSL sample. These samples were analyzed for concentrations of K, U, Th, and Rb using high-resolution gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), or atomic emission spectroscopy (ICP-AES). The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and final dose rate values were calculated using equations from Aitken (1998). All OSL ages (Table 4.1) are presented in calendar years before 2010.

In addition to OSL samples, six AMS ^{14}C samples were collected and submitted to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) for AMS dating, a well-established Quaternary dating technique (review in Beukens, 1992). All AMS ^{14}C samples from this study were derived from bulk organic material collected within buried soils (Ab horizons) encountered in the dune field. Prior to submission, samples were oven-dried, any modern rootlets removed, and crushed to insure complete combustion during dating analysis. AMS ^{14}C ages were calibrated to calendar years using Calib 6.1.0 (Stuiver and Remier, 1993) and are reported in Table 4.2.

4.3. Results

4.3.1. OSL ages

All OSL samples reported herein, with one exception, are chronologically consistent with their stratigraphy and, where applicable, are corroborated with ^{14}C ages (Tables 4.1; 4.2). The single OSL age removed from the chronology (LE 1-2) occurred at the LE 1 site and was the result of a contaminated sample (see discussion in section 4.4.1). Ages from the SD 2 and SD 3 sites also appear to be inverted as presented in Table 4.1 and Figure 4.36, however, the lower (second) age from each site was collected

Table 4.1. Equivalent dose, dose rate, and age estimates for the Arkansas River dunes

Field Site	OSL Sample	Lab #	Depth (m)	Dose Rate (Gy/ka)	De (Gy) ± Std. Err.	Aliq. (n)[a]	Optical Age ± 1σ
Pyle Ranch Site 1 (N 37.71100, W 99.53980)							
	BP 1-1	UNL-2566	0.8	4.60 ± 0.29	0.12 ± 0.01	23/24	30 ± 5
	BP 1-2	UNL-2567	1.8	4.04 ± 0.23	0.88 ± 0.05	21/24	220 ± 20
	BP 1-3	UNL-2568	3.4	4.38 ± 0.29	1.24 ± 0.07	23/24	280 ± 30
Pyle Ranch Site 2 (N 37.71855, W 99.53522)							
	BP 2A-1	UNL-2569	0.6	4.11 ± 0.22	0.14 ± 0.02	20/24	34 ± 6
	BP 2A-2	UNL-2570	2.0	3.91 ± 0.23	0.75 ± 0.03	24/24	190 ± 20
	BP 2B-1	UNL-2571	1.6	3.96 ± 0.22	0.13 ± 0.03	17/24	33 ± 7
	BP 2B-2	UNL-2572	2.6	4.16 ± 0.24	0.87 ± 0.04	22/24	210 ± 20
Pyle Ranch Site 3 (N 37.71862, W 99.53527)							
	BP 3-1	UNL-3007	3.4	3.00 ± 0.21	0.69 ± 0.06	21/23	230 ± 30
	BP 3-2	UNL-3008	6.3	3.02 ± 0.22	0.44 ± 0.03	20/26	150 ± 20
Pyle Ranch Site 4 (N 37.71892, W 99.53458)							
	BP 4-1	UNL-3009	2.9	2.72 ± 0.11	> 150	--	> 55,100b
	BP 4-2	UNL-3010	1.1	3.22 ± 0.23	2.18 ± 0.16	21/23	680 ± 80
Pyle Ranch Site 5 (N 37.73425, W 99.52483)							
	BP 5-1	UNL-3011	1.3	3.33 ± 0.20	1.98 ± 0.18	24/28	600 ± 70
	BP 5-2	UNL-3012	1.4	3.09 ± 0.22	85.4 ± 4.5	23/27	27,600 ± 2700
Gross Landfill (N 37.95360, W 101.00220)							
	GL 1-1	KSU-0006	0.8	4.19 ± 0.24	0.48 ± 0.09	2/2	90 ± 3
	GL 2-2	UNL-2564	1.5	5.19 ± 0.30	0.89 ± 0.11	20/24	170 ± 20
	GL 1-3	KSU-0008	2.9	4.36 ± 0.24	1.54 ± 0.14	6/6	350 ± 30
	GL 1-4	KSU-0009	4.3	4.23 ± 0.23	1.95 ± 0.36	6/6	460 ± 40
	GL 1-5	KSU-0010	5.2	4.57 ± 0.25	2.02 ± 0.28	6/6	440 ± 70
	GL 1-6	KSU-0011	6.3	4.18 ± 0.23	2.44 ± 0.22	6/6	580 ± 60
	GL 1-7	KSU-0012	6.7	4.19 ± 0.23	2.56 ± 0.21	6/6	610 ± 60
	GL 1-8	KSU-0013	7.3	4.17 ± 0.23	55.34 ± 7.5	6/6	13,260 ± 1,950
	GL 1-10	KSU-0015	11.9	3.87 ± 0.22	57.54 ± 2.4	6/6	14,850 ± 1,479
Price Ranch Site 3 (N 37.79910, W 101.15691)							
	PRI 3-1	UNL-3366	6.2	3.04 ± 0.20	2.7 ± 0.1	21/27	890 ± 80

Land East Site 1 (N 37.84663, W 101.42138)						
LE 1-1	UNL-3013	3.2	2.88 ± 0.19	2.57 ± 0.39	24/28	890 ± 150
LE 1-2	UNL-3014	6.3	2.98 ± 0.20	0.66 ± 0.10	21/27	220 ± 40
Land East Site 2 (N 37.84637, W 101.42110)						
LE 2-1	UNL-3015	6.3	2.91 ± 0.22	29.6 ± 1.7	23/23	10,200 ± 1100
LE 2-2	UNL-3016	6.7	2.93 ± 0.21	122.6 ± 4.3	27/33	41,800 ± 3800
Land East Site 3 (N 37.84490, W 101.41988)						
LE 3-1	UNL-3017	5.8	2.80 ± 0.19	0.49 ± 0.07	24/26	170 ± 30
Land East Site 4 (N 37.84512, W 101.41913)						
LE 4-1	UNL-3018	3.3	2.93 ± 0.28	66.4 ± 2.3	23/28	22,700 ± 2500
LE 4-2	UNL-3019	4.8	2.51 ± 0.17	108.1 ± 5.2	26/33	43,100 ± 4000
Land East Site 5 (N 37.84512, W 101.41913)						
LE 5-1	UNL-3020	5.0	3.11 ± 0.20	0.41 ± 0.03	20/30	130 ± 20
P5 Ranch Site 1 (N 37.87472, W 101.47675)						
GM 1-1	UNL-2995	3.3	3.08 ± 0.21	1.61 ± 0.06	23/25	520 ± 50
GM 1-2	UNL-2996	4.2	2.86 ± 0.18	29.5 ± 1.4	20/31	10,300 ± 900
P5 Ranch Site 2 (N 37.89283, W 101.47717)						
GM 2-1	UNL-2997	0.8	3.46 ± 0.22	6.88 ± 0.12	23/28	1990 ± 160
Syracuse Feedlot (N 37.97770, W 101.72635)						
SYF 1-1	UNL-3382	1.8	3.60 ± 0.19	88.7 ± 6.6	25/42	24,700 ± 2500
SYF 1-2	UNL-3383	2.3	3.02 ± 0.19	88.8 ± 6.8	27/42	29,400 ± 3200
Tarbet Quarry East (N 37.96270, W 101.75507)						
TB 1-1	UNL-2998	0.8	3.44 ± 0.21	0.66 ± 0.04	22/26	190 ± 20
Tarbet Quarry West (N 37.96242, W 101.76182)						
TB 2-1	UNL-2999	0.6	3.54 ± 0.21	1.77 ± 0.10	22/28	500 ± 50
TB 2-2	UNL-3000	1.3	3.18 ± 0.20	3.68 ± 0.23	22/23	1160 ± 110
Syracuse ATV Park Site 1 (N 37.95142, W 101.77827)						
SD 1-1	UNL-2989	5.0	2.91 ± 0.27	12.4 ± 0.9	20/28	4250 ± 520
Syracuse ATV Park Site 2 (N 37.94648, W 101.79257)						
SD 2-1	UNL-2990	3.4	2.95 ± 0.18	0.73 ± 0.07	22/28	250 ± 30
SD 2-2	UNL-2991	6.8	3.03 ± 0.19	0.60 ± 0.04	21/25	200 ± 20
Syracuse ATV Park Site 3 (N 37.95040, W 101.80758)						
SD 3-1	UNL-2992	3.2	3.00 ± 0.19	0.80 ± 0.06	21/25	270 ± 30
SD 3-2	UNL-2993	6.5	3.06 ± 0.20	0.74 ± 0.06	21/25	240 ± 30
Syracuse ATV Park Site 4 (N 37.95317, W 101.79663)						
SD 4-1	*UNL-2994*	*1.2*	*3.21 ± 0.20*	*1.11 ± 0.23*	*20/25*	*350 ± 80*

Wharton Ranch Site 1 (N 37.95657, W 101.98315)							
	WH 1-1	UNL-3001	3.3	3.24 ± 0.19	0.40 ± 0.04	21/28	120 ± 20
	WH 1-2	UNL-3002	6.3	2.84 ± 0.19	44.6 ± 1.8	22/28	15,700 ± 1400
Wharton Ranch Site 2 (N 37.95692, W 101.98733)							
	WH 2-1	UNL-3003	0.8	3.00 ± 0.20	37.6 ± 1.5	20/28	12,600 ± 1100
Wharton Ranch Site 3 (N 37.95760, W 101.98750)							
	WH 3-1	UNL-3004	0.7	3.13 ± 0.21	18.3 ± 0.6	21/23	5860 ± 510
	WH 3-2	UNL-3005	0.9	3.19 ± 0.21	27.9 ± 1.1	21/23	8800 ± 800
Wharton Ranch Site 4 (N 37.95777, W 101.98520)							
	WH 4-1	UNL-3006	1.0	2.95 ± 0.19	40.8 ± 0.7	20/23	13,800 ± 1100

[a] Accepted disks/total disks.
[b] Sample was too old to produce a meaningful age; this should be considered a minimum age estimate for the sample.

Table 4.2. AMS Radiocarbon ages from the Arkansas River dunes

Field Site	^{14}C Sample	Lab ID	δ^{13}C ‰	Age (^{14}C yrs BP)[a]	Calibrated Age (cal yrs BP)[b]
Ford County Site 1 (N 37.70417, W 100.02500)					
	FO 1-1R	ISGS 5239	-16.5	19,130 ± 150	22,870 ± 480
Ford County Site 1 (N 37.67500, W 100.93333)					
	FO 1-2R	ISGS 5077	-15	19,430 ± 200	23,130 ± 600
Ingalls Feedlot (N 37.84997, W 100.48386)					
	ING 1-1R	OS-91050	-15.47	20,400 ± 230	24,190 ± 380
	ING 1-2R	OS-91059	-13.8	25,300 ± 200	29,930 ± 160
Gross Landfill (N 37.95360, W 101.00220)					
	GL 1-1R	OS-83174	-22.95	15,200 ± 90	18,200 ± 160
Wharton Ranch Site 4 (N 37.95777, W 101.98520)					
	WH 4-1R	OS-83168	-14.7	4240 ± 30	4830 ± 25

[a] AMS radiocarbon ages.
[b] Ages calibrated with Calib 6.1.0 (Stuiver and Reimer, 1993), shown with 2σ error range.

downslope from the upper age, not directly below, and, therefore, ages from these sites do not truly represent a continuous stratigraphic profile. Additionally, these two sets of ages are within their 1σ errors, rendering them reliable. Finally, OSL ages which have not been fully analyzed (n=26), are presented in the figures as ages without data (n.d.) and are not included in the discussion.

4.3.2. Site stratigraphy and chronology

Stratigraphic and chronologic data for the individual sites sampled in this study are outlined under the following subheadings, and latitude and longitude coordinates for each site are in Table 4.1.

4.3.2.1. Pyle Ranch sites (BP 1–5)

The Pyle Ranch and sample sites within are located on the eastern boundary of the ARD and the neighboring Great Bend Sand Prairie (Fig. 4.2; Fig. 4.5). Though Arbogast (1996) and Arbogast and Johnson (1998) mapped these dunes as part of the Great Bend Sand Prairie, they did not conduct subsurface investigations. Four dunes were sampled within the Pyle Ranch: BP 1, BP 2, BP 3 (including BP 4), and BP 5 (Fig. 4.5).

BP 1, a small blowout, exposes ~2 m of cross-bedded aeolian sand with a weakly developed surface soil and a slightly better-developed buried soil, ~20 cm thick, at a depth of ~80 cm. Two OSL samples (BP 1-1, 1-2) collected from aeolian sand above and below the buried soil yielded ages of 30 ± 5 and 220 ± 20 years ago, respectively. A bucket auger was used at the base of the profile to sample sediment to a depth of ~3.7 m. An additional OSL sample (BP 1-3), collected at 3.4 m, dated to 280 ± 30 years ago.

The BP 2 site is a large blowout ~1.5 km northeast of BP 1 measuring ~400 m in width and ~500 m long. Remnant crests on the western and eastern side of a deflated dune blowout each expose about 2.5 m of aeolian sediment. The western crest exposure (BP 2A) is 2.5 m deep and contains a very thin surface soil and a ~20 cm thick buried

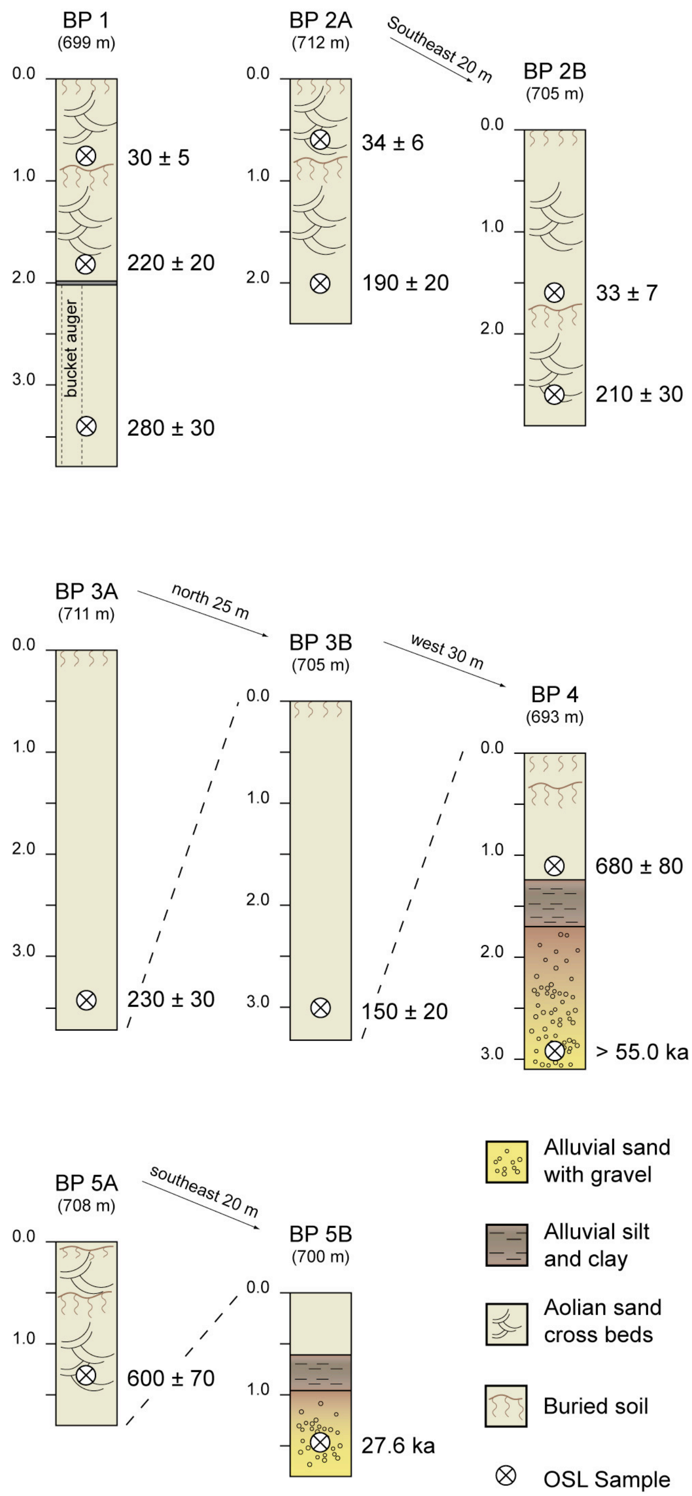

Figure 4.5. Stratigraphic profiles of the Pyle Ranch 1–5 sites. Ages are presented in years or ka years before 2010.

soil. An OSL sample (BP 2A-1) above this soil dated to 34 ± 6 years ago, and another below dated to 190 ± 20 years ago (BP 2A-2). The eastern crest exposure (BP 2B) is ~2.9 m deep and contains a similar surface and buried soil to that found at BP 2A. An OSL sample (BP 2B-1) above this soil yielded an age of 33 ± 7 years ago, and another below yielded an age of 210 ± 30 years ago (BP 2B-2).

A bucket auger was used to sample the crest of a tall dune at the BP 3 site (Figs. 4.6, 4.7). Other than a weak surface soil, no visible changes in sediment were noted. An OSL sample (BP 3-1) collected at a depth of 3.4 m dated to 230 ± 30 years ago. A second auger hole was cored from a saddle in the dune ~25 m north of the crest, and, as before, no changes in stratigraphy were noted other than a weakly developed surface soil; an OSL sample (BP 3-2) collected at a depth of 3 m dated to 150 ± 20 years ago. Thirty meters west of the BP 3 site is the corresponding dune swale BP 4 site, ~18 m below the BP 3 dune crest (Fig. 4.7). The upper 60 cm of sediment at the BP 4 site is characterized by ~10 cm of surface soil development, followed by ~30 cm of aeolian sand, and finally a buried soil ~20 cm thick. Aeolian sediment continued below this buried soil to ~1.3 m, where a layer of alluvial silt and clay ~30 cm thick was encountered. Below the fine-grained alluvium was highly oxidized, alluvial sands and gravels, which continued to the bottom of the hole at 3.1 m. Two OSL samples were collected from this profile, one in aeolian sand above the alluvial contact at 1.1 m and another in the alluvium at 2.9 m. The aeolian sample (BP 4-1) dated to 680 ± 80 years ago, whereas the alluvial sample (BP 4-2) exceeded the upper age limits of OSL—a minimum age of >55,000 years ago was estimated.

The final site in the Pyle Ranch study area is another blowout, ~5 km north of the BP 3 site, with ~1.8 m of exposed stratigraphy within remnants of a deflated dune (Figs. 4.5, 4.8). No surface soil was found at this site; instead, the dune surface is currently being buried by modern aeolian sedimentation, evidenced by an *Opuntia sp.* cacti buried beneath ~10 cm of sand. A buried soil, ~20 cm thick, was found at a depth of 50 cm, and

Figure 4.6. Auger sampling at the BP 3 site, the crest of one of the tallest dunes in the area (arrow).

Figure 4.7. Auger sampling at the BP 4 site, an interdune basin. The BP 3 site is visible in the background.

an OSL sample (BP 5-1) collected below this soil at 1.3 m in cross-bedded aeolian sand dated to 600 ± 70 years ago. Bucket auger sampling in the bottom of this blowout, ~20 m southeast and downslope ~8 m from the blowout crest, recorded ~60 cm of aeolian sand, a layer of alluvial silt and clay, and a subsequent layer of alluvial sands and gravels. An OSL sample (BP 5-2) collected from the alluvial sands and gravels yielded an age of 27,600 ± 2700 years ago.

Figure 4.8. Auger sampling within the blowout basin of the BP 5 site; the profile created in the wall of the blowout can be seen in the background (arrow).

4.3.2.2. Ingalls Feedlot (IGL 1)

The IGL site located on a north-facing loess escarpment on the northern border of the Arkansas River valley (Fig. 4.2), is a 14 m high loess exposure containing stacked buried soils (Figs. 4.9; 4.10). While not part of the ARD proper, loess deposits in proximity to the ARD may also contain important information on the timing of past aeolian activity.

Though the upper ~7 m of the exposure was not investigated in detail, the general stratigraphy is consistent with Holocene-aged loess deposits found throughout much of Kansas (e.g., Johnson and Arbogast, 1994; Johnson 2003a; 2003b; Johnson and Woodburn, 2011). Approximately 7 m of the lower loess, accessible through a road cut, is characterized by ~1.3 m of loess, which abruptly transitions to a buried soil ~70–80 cm thick (Fig. 4.10). Below this buried soil is loess, which becomes increasingly calcareous with depth. An OSL sample was collected from the loess above the buried soil (IGL 1-1), though this sample is yet to be analyzed. Additionally, two AMS ^{14}C samples taken directly from the upper 5 cm and lower 5 cm of the soil (IGL 1-1R; IGL 1-2R), yielded calibrated ages of 24,255 ± 310 years BP (20,400 ± 230 ^{14}C years BP) and 30,234 ± 125 years BP (25,300 ± 200 ^{14}C years BP), respectively, which are coeval with ages of the Gilman Canyon Formation in Kansas and Nebraska (Johnson et al., 2007; Aleinikoff et al., 2008; Muhs et al., 2008).

4.3.2.3. Ingalls Gravel Pit (IG 1)

The IG site is a gravel pit ~3 km south of Ingalls, Kansas, characterized by a 5 m high exposure of cross-bedded aeolian sediment above ~6 m of gravelly alluvium (Fig. 4.9; 4.11). Distinctive bedding bounding surfaces were observed in the aeolian sediment, which visibly divided the sediment into four aeolian units (A1–4), possibly indicating multiple generations of dunes. Four OSL samples were collected from each of the aeolian units at depths of 1.2 m (IG 1-1), 2.8 m (IG 1-2), 3.7 m (IG 1-3), and 4.7 m (IG 1-4); an additional OSL sample was collected at 5.1 m (IG 1-5) in gravelly alluvium, immediately below a thin layer of alluvial silts and clays, which mark the top of the alluvium. OSL samples from this site have not yet been analyzed.

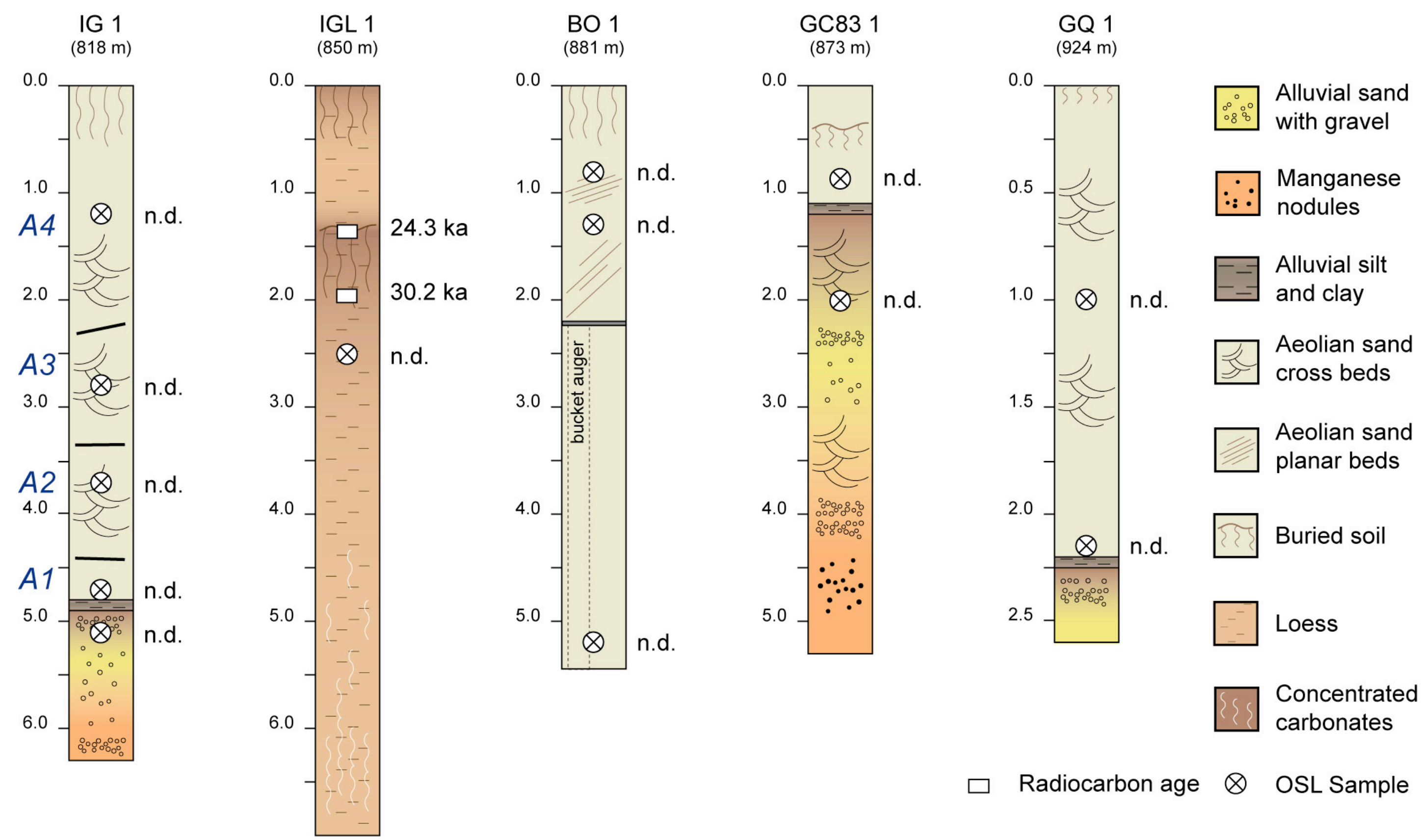

Figure 4.9. Stratigraphic profiles of the IG 1, IGL 1, BO 1, GC83 1, and GQ 1 sites. Radiocarbon ages are presented in ka years before present.

Figure 4.10. Fourteen meters of loess deposits at the Ingalls Feedlot site, including the soil sampled for AMS ^{14}C dating (arrow).

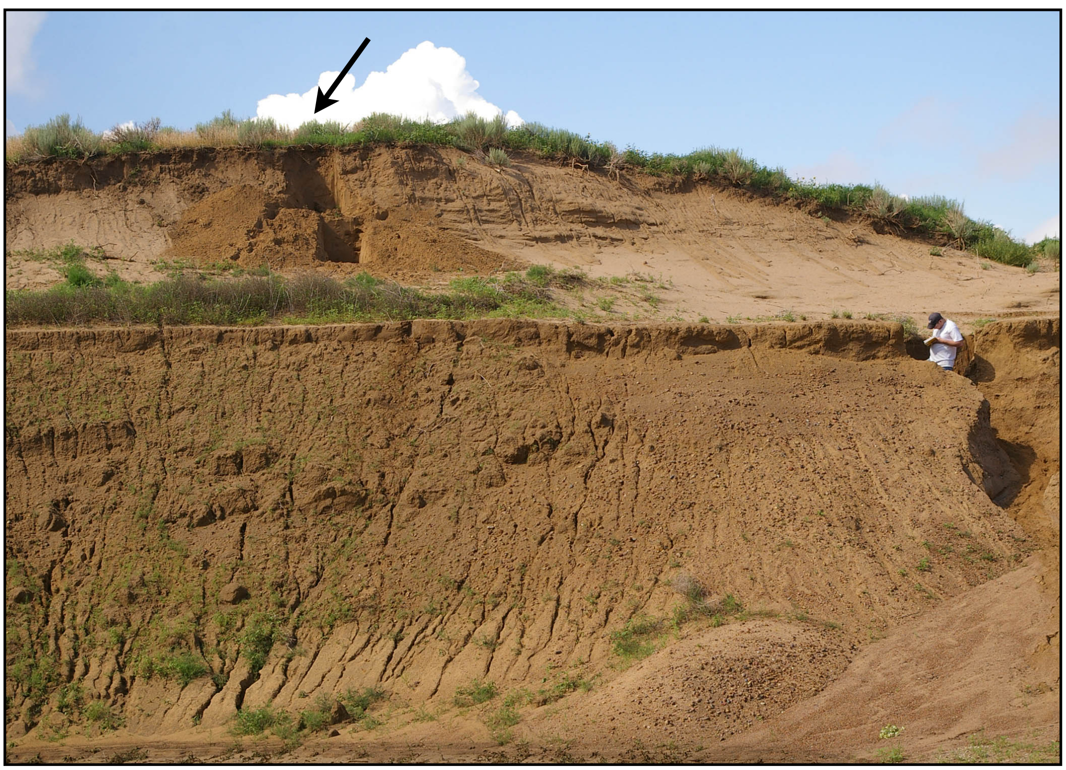

Figure 4.11. Stepped profile at the IG 1 site (arrow). An aeolian dune is seen overlying alluvium (beginning at the approximate position of AFH's head).

4.3.2.4. Brookover Ranch (BO 1)

Low relief (>5 m) dome dunes cover the Brookover Ranch study area, which is located ~20 km southeast of Garden City, Kansas. A two-track, transmission-line service road provided access to small road cuts, which exposed dune stratigraphy. The BO 1 site is a southeast-facing road cut characterized by ~2 m of exposed eolian sand with a moderately developed (~40–50 cm thick) surface soil in planer cross beds, which dip ~5º towards the southeast—an OSL sample was collected within this sediment at a depth of 80 cm (BO 1-1) (Fig. 4.9; 4.12). An abrupt change in the bedding occurred at ~1.5 m with planer cross beds which now dipped ~30º towards the south, and an additional OSL sample was collected at 1.3 m at this transition. The profile was extended to a depth of ~5.4 m using a bucket auger, though no additional changes in stratigraphy were noted. An

Figure 4.12. The BO 1 site.

OSL age was collected from the base of the bucket auger hole at 5.3 m. None of the OSL samples from this site have been analyzed yet.

4.3.2.5. Garden City Sand Pit (GC83 1)

The GC83 site (Fig. 4.9), a gravel quarry located ~5 km south of Garden City, Kansas, east of old State Highway 83, exposes ~19 m of alluvium topped by ~1.2 m of aeolian sediment. A 5.5 m profile was created in the southeast face of the quarry exposing the aeolian sediments and the upper beds of the underlying alluvium (Fig. 4.13). At the surface of the aeolian sediment is a thin (<10 cm) soil with a somewhat better developed buried soil at ~40 cm. Aeolian sediment transitions to clay- and silt-rich alluvium at ~1.3 m, and then to cross-bedded gravelly alluvium. Several packages of alluvium are noted within the quarry face and include highly oxidized zones with abundant manganese

Figure 4.13. The GC83 1 site profile (arrow). Aeolian sediment occurs above ~19 m of exposed alluvium.

nodules. Two OSL samples (GC83 1-1, 1-2) were collected from the GC83 1 site: one within the aeolian sediment at ~90 cm and another within an upper zone of cross-bedded alluvium at 2 m. None of the OSL samples from this site have yet been analyzed.

4.3.2.6. Gross Landfill (GL 1)

The GL 1 site (Fig. 4.14) is a recently excavated landfill cell proximal to the Arkansas River, ~25 km southwest of Garden City, Kansas (Fig. 4.2). A ~13 m high profile was created in the west face of the landfill exposing three aeolian units overlying three alluvial units (Figs. 4.14, 4.16). The upper aeolian unit (A3) is characterized by a weakly developed surface soil (<20 cm) underlain by cross- and planar-bedded aeolian sediment ~3 m thick. A stratigraphic break was exposed at 3.0 m separating A3 from A2, which is another ~3 m thick section of cross-bedded aeolian sediment. Three OSL samples (GL 1-1, 1-2, 1-3) collected from A3 at depths of 0.8, 1.5, and 2.9 m yielded ages of 90 ± 3, 170 ± 20, and 350 ± 30 years ago. Two OSL samples (GL 1-4, 1-5) collected from A2 at 4.3 and 5.2 m yielded ages of 460 ± 40 and 440 ± 70 years ago.

At 6 m, stratigraphy changed abruptly from cross-bedded aeolian sand to laminated, organic-rich, fine-grained sediments, which are interpreted as interdune ponded sediments (Fig. 4.15). An OSL sample (GL 1-6) collected from the top 5 cm of these sediments yielded an age of 580 ± 60 years ago. Immediately below the interdune sediments is the lowermost aeolian unit (A1), a 80 cm thick zone of aeolian sand—an OSL (GL 1-7) sample collected from A1 dated to 610 ± 60 years ago. Alluvium appeared at ~7.1 m and continues downward through the rest of the profile. In general, alluvial sediments at the GL 1 site are characterized by thin layers (10-20 cm) of silt and clay, which transition abruptly to thick (~1–3 m) zones of coarse sediment. These zones (F1–3) contain abundant cross-bedded sand and gravel that gradually fine upward, for example, from granules or very coarse sand to fine sand. Optically stimulated luminescence samples were collected from each of the alluvial fills, though only two samples (GL 1-8,

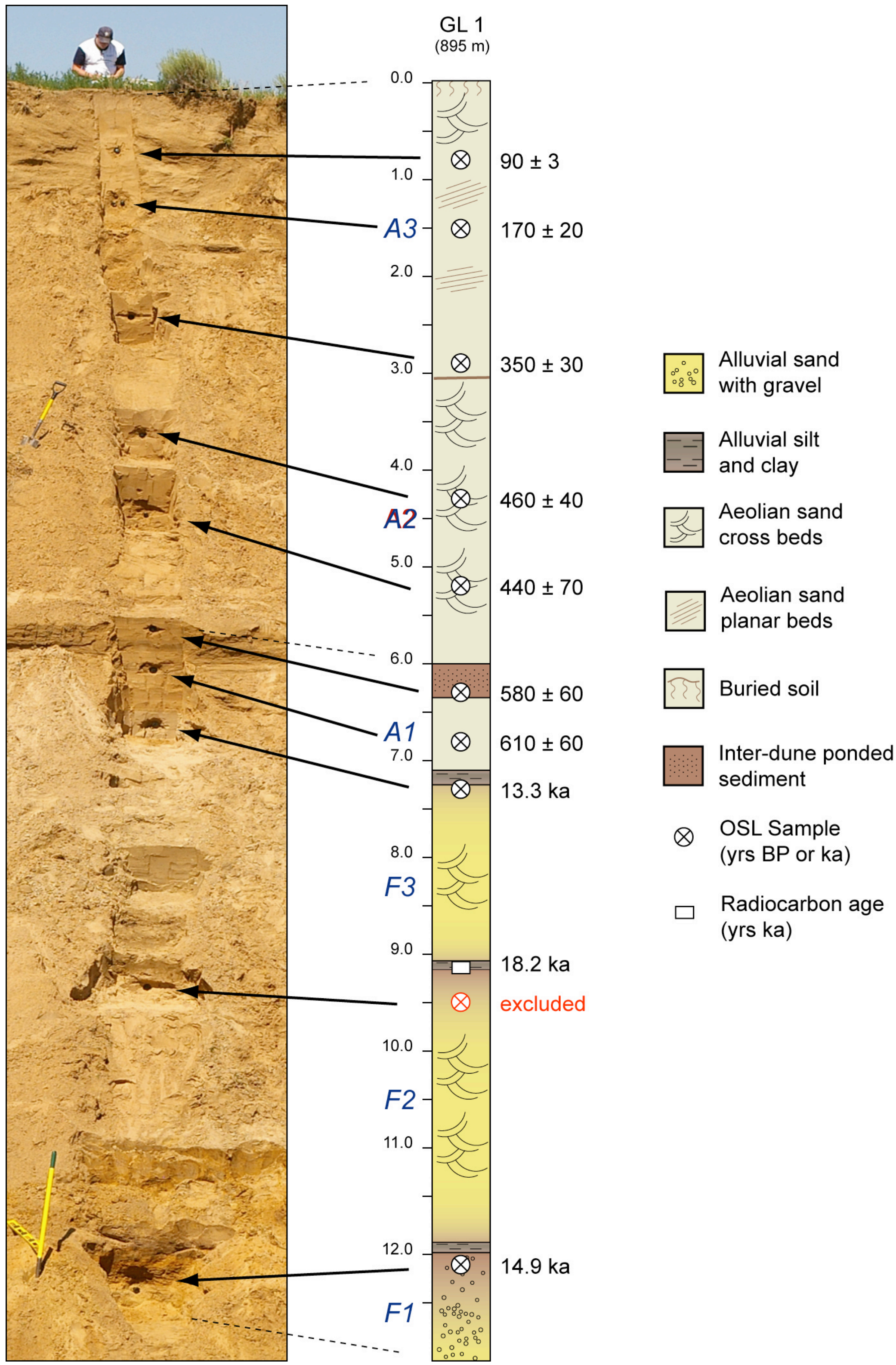

Figure 4.14. Stratigraphic profile of the GL 1 site. Ages are presented in years or ka years before 2010. The sample at 9.5 m was excluded due to low concentrations of datable quartz, which resulted in unreliable age estimates.

Figure 4.15. Fine-grained sediments interpreted as interdune ponded sediments. Approximate scale between the two sample marks (arrows) is ~80 cm.

Figure 4.16. Stepped profile at the Gross Landfill site (arrow).

1-10) yielded reliable ages, which indicate alluvial deposition between 13,260 ± 1950 and 14,850 ± 1479 years ago. Additionally, a ^{14}C age (GL 1-1R) obtained from charcoal found within the fine-grain sediment between F3 and F2 dated 18,200 ± 160 calibrated years BP (15,200 ± 90 ^{14}C yrs BP).

4.3.2.7. J & O Cattle Ranch sites.

The JOC sites (Fig. 4.17) are situated ~25 km southwest of Garden City, Kansas (see Fig. 4.3C), within the center of the widest part of the ARD, an area characterized by many large, flat-bottom basins surrounded by low-relief (<10 m) parabolic and dome dunes. These features are deflation basins, which were the source areas of adjacent dunes. This interpretation was confirmed by a local landowner who recounts the basin area serving as a sand source for the nearby parabolic dunes during the 1950s (Bob Jones, 2010: *personal communication*).

The JOC 1 site is located in the blowout of a parabolic dune immediately adjacent to a deflation basin (Fig. 4.18). A ~4 m profile was created in the dune, which exposed a thin buried soil, similar in characteristics to the pre-1930's soils documented in other parts of the dune field (i.e., BP sites), and aeolian sediment characterized as thinly laminated sand that grades to larger planar beds with depth. Clay lamellae are observed throughout the profile as are packages of coarser-grained, leached sand (Fig. 4.19). Two OSL samples (JOC 1-1, 1-2) were collected within this profile at 1.8 m and at 4.2 m, but neither of these ages has yet been analyzed.

The JOC 2 site is located only 20 m west of the JOC 1 site, in an older, now stabilized blowout depression (Fig. 4.20). A bucket auger was used to collect two OSL samples, the first collected at 4.1 m in aeolian sand, directly above a thick (~1 m), well developed buried soil with abundant fine-grained particles and visible accumulations of $CaCO_3$ (JOC 2-1). A second OSL sample was collected in sandy sediment below this soil at 6.1 m. Neither of these OSL ages has yet been analyzed.

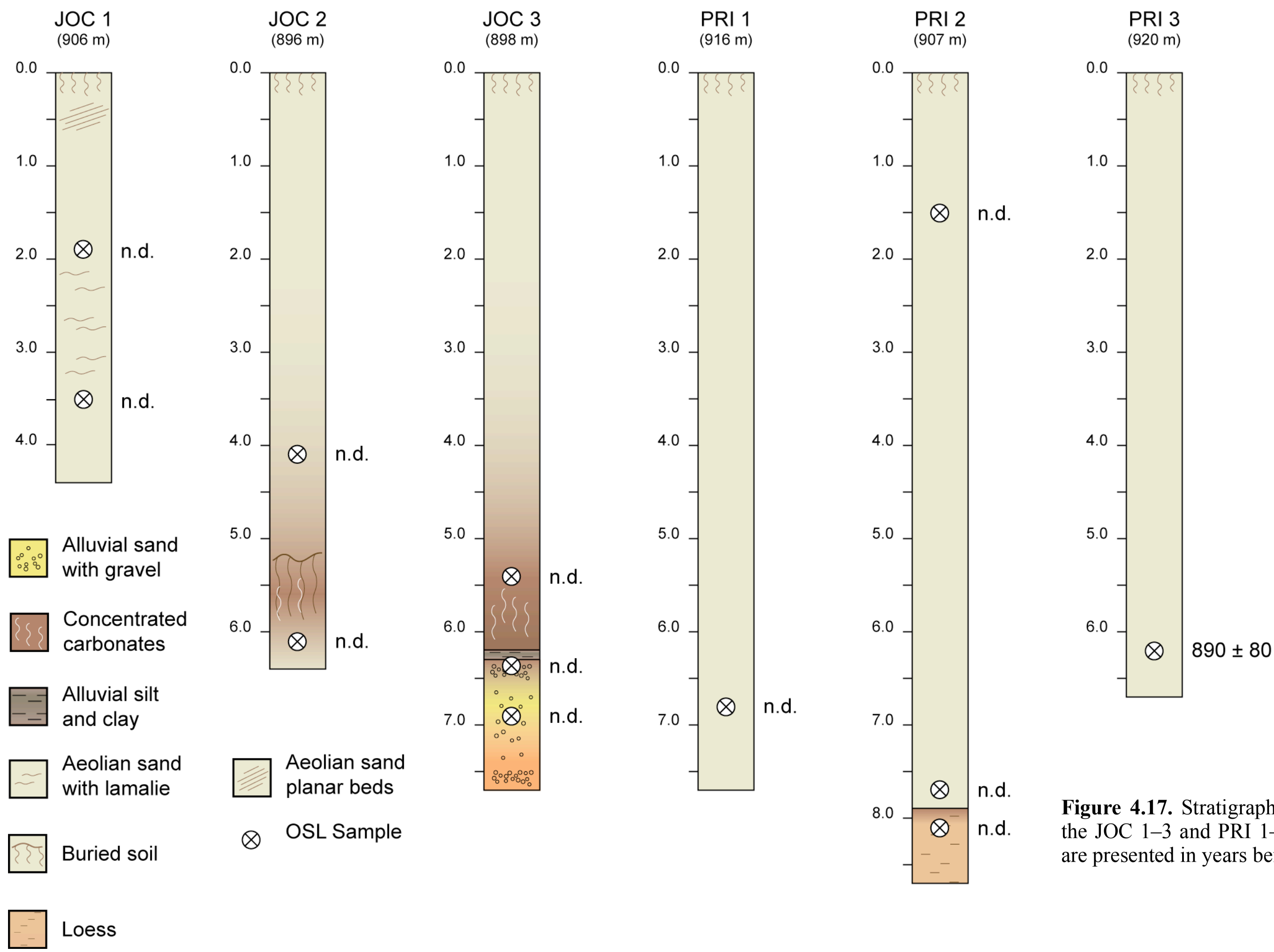

Figure 4.17. Stratigraphic profiles of the JOC 1–3 and PRI 1–3 sites. Ages are presented in years before 2010.

Figure 4.18. Stepped profile at the JOC 1 site (arrow). The adjacent deflation basin is pictured in the background right.

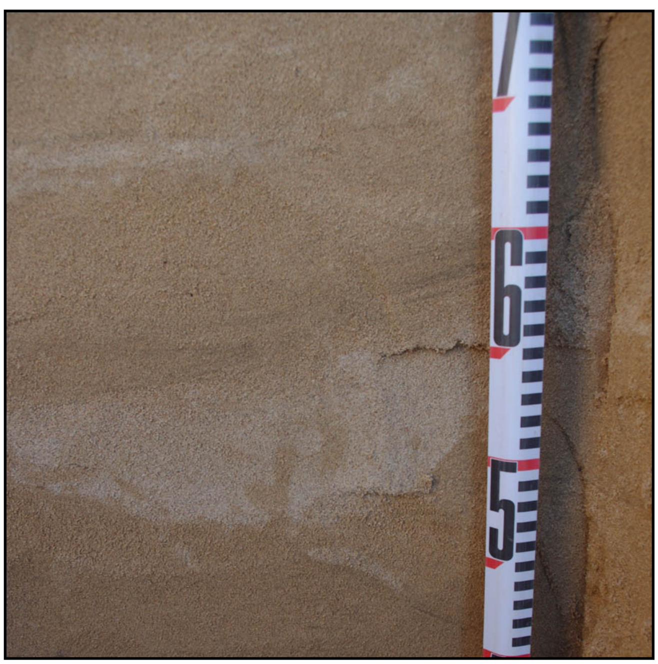

Figure 4.19. Examples of fine laminations and leached sediment packages documented at the JOC 1 site.

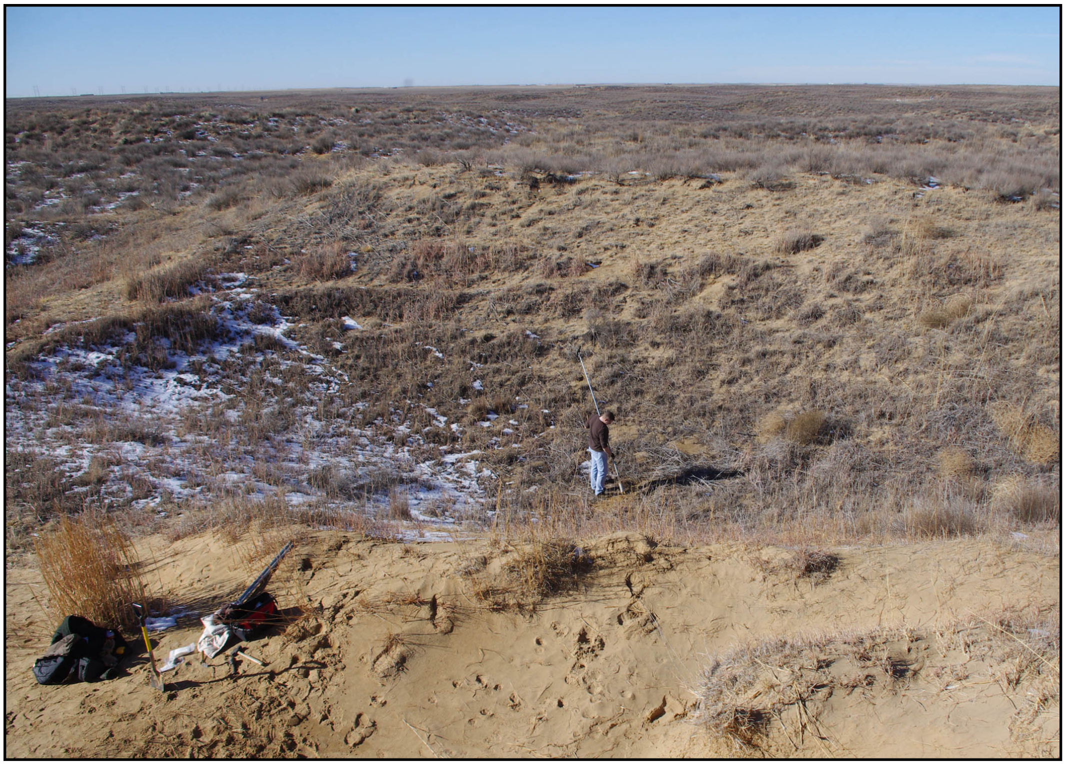

Figure 4.20. The JOC 2 site located in a stabilized blowout. (JOC 1 site: photographer's location).

A third site at the J & O Cattle Ranch (JOC 3) is located ~200 m east of the JOC 1 site in the nearby deflation basin (Fig. 4.21). A bucket auger was used to document the stratigraphy at this site and to collect OSL samples. Aeolian sediments occurred to a depth of ~5.6 m, at the abrupt transition to alluvium. This transition was marked by a thick (~60 cm) layer of highly calcified alluvial silts and clays, underlain by oxidized gravelly alluvium, which was encountered to the base of the auger hole at 7 m. Three OSL samples were collected from this site, the first at the base of the aeolian sediment ~5.4 m (JOC 3-1), the second below the calcified silt and clay at 6.3 m (JOC 3-2), and the third within the gravelly alluvium at 6.9 m (JOC 3-3). None of these OSL samples have yet been analyzed.

Figure 4.21. The JOC 3 site. The JOC 1 site dune is the isolated ridge in the right background of this image.

4.3.2.8. Price Ranch sites (PRI 1–3)

The PR sites (Fig. 4.17), located on the southern edge of the ARD ~35 km south of Garden City, Kansas (Fig. 4.2), are the most distal from the river of all the sites sampled in this study. The PR 1 site is located at the crest of a tall dome-shaped dune (Fig. 4.22), which is a remnant crest of a north-trending parabolic dune because other dunes in the area have distinctive north-trending parabolic morphologies. Auguring was used to document dune stratigraphy and collect OSL samples. No observable changes in aeolian sediment were documented within the auger hole, and an OSL sample (PRI 1-1) was collected from a depth of 6.8 m . This sample has not yet been analyzed.

Sampling continued by moving downslope and ~50 m northeast of the PRI 1 site to an associated interdune area (PRI 2) (Fig. 4.23). Here again, auguring was used to document stratigraphy and collect OSL samples. Aeolian sand was revealed throughout

Figure 4.22. The PRI 1 site (arrow).

Figure 4.23. The PRI 2 site.

most of the auger hole to a depth of ~7.7 m, where sandy aeolian sediment transitioned to silt-dominated sediment, observed to the bottom of the auger hole at ~8.2 m. This silty sediment is interpreted as loess, probably similar to that documented by earlier studies south of Garden City, Kansas, only ~10 km east of the PRI 2 site (Simonett, 1960; Olson et al., 1997). Three OSL samples were collected from the PRI 2 site, the first in aeolian sand at 1.5 m (PRI 2-1), the second at the sand-loess transition (PRI 2-2), and the third at the base of the auger hole (PRI 2-3). No OSL samples from this site have yet been analyzed.

Auguring was used to document dune stratigraphy and collect OSL samples at the PRI 3 site, ~10 km west of the PRI 1 and PRI 2 sites. This site is also located at the crest of a tall dome-shaped dune (Fig. 4.24). No observable changes in aeolian sediment were documented within the auger hole to a depth of ~6.8 m. An OSL sample (PRI 3-1) from a depth of 6.2 m dated to 890 ± 80 years ago.

Figure 4.24. Auguring at the PRI 3 site.

4.3.2.9. Grant County Gravel Pit (GQ 1)

The GQ site (Fig. 4.9), located in an abandoned gravel quarry at the very northern edge of the ARD ~1 km south of Deerfield, Kansas (Fig. 4.2), is characterized by ~2.2 m of aeolian sediment underlain by ~8 m of alluvium. A 2.7 m profile created in the southern face of the quarry (Fig. 4.25) exposed a surface soil thicker (>20 cm) than most other dune field surface soils, which was further underlain by cross-bedded aeolian deposits. The alluvial contact, encountered at ~2.25 m, was characterized by a thin layer of silty clay over sands and gravels. Though not included in the profile, alluvial sands and gravels were exposed at the base of the quarry face. Two OSL samples were taken in the aeolian sediment at 1 m (GQ 1-1) and directly above the alluvial contact at 2.1 m (GQ 1-2), respectively. OSL samples from this site have not yet been analyzed.

Figure 4.25. Stepped profile at the GQ 1 site (arrow).

4.3.2.10. Land East sites (LE 1–5)

The Land East sites (Fig. 4.26), located on a large cattle ranch south of the Arkansas River about halfway between Lakin and Kendall, Kansas (Fig. 4.2), occur in an area dominated by transverse dunes, which have been overprinted by younger generations of parabolic dunes (Figs. 4.27; 2.28). Dune stratigraphy and OSL samples were collected from five sites, which create a transect across two consecutive transverse dune ridges (Fig. 4.26). Auguring at the LE 1 site, the northern of the two sampled transverse dunes ridges (Fig. 4.29), documented ~7 m of aeolian sand with no noticeable changes in stratigraphy. Two OSL samples collected from this site at 3.2 m (LE 1-1) and 6.7 m (LE 1-2) yielded ages of 890 ± 150 and 220 ± 40 years ago, respectively. The LE 2 site is located in a blowout ~1 m above the interdune basin southeast and downslope from the LE 1 site (Fig. 4.30). Stratigraphy at this site consisted of ~6.4 m of aeolian sediment, which rapidly transitioned into gravelly alluvium by ~6.5 m. Two OSL samples were collected from the LE 2 site, the first within aeolian sediment at 6.3 m (LE 2-1), which yielded an age of 10,200 ± 1100 years ago, and the second within the alluvium at 6.7 m (LE 2-2), which was dated to 41,100 ± 3800 years ago.

The LE 3 and LE 4 sites are comparable to the LE 1 and LE 2 sites in that they are a transverse dune crest site and basal site sampled from a nearby blowout just above an interdune basin (Figs. 4.31; 4.32). Stratigraphy of the LE 3 site (dune crest) consisted of ~6 m of aeolian sediment with no noticeable changes in stratigraphy, and an OSL sample collected from a depth of 5.8 m (LE 3-1) dated to 170 ± 30 years ago. The LE 4 site is located ~30 m east and downslope of the LE 3 site, and auguring this blowout revealed ~2.8 m of aeolian sand, which transitioned abruptly to oxidized alluvial sand and gravels ~1 m thick. Encountered below the oxidize alluvial fill was pale yellow sand that continued to the bottom of the auger hole. Two OSL samples from within the alluvial sediments, one from the oxidized alluvium (LE 4-1) and another from the lower alluvial fill (LE 4-2), dated to 22,700 ± 2500 and 43,100 ± 4000 years ago.

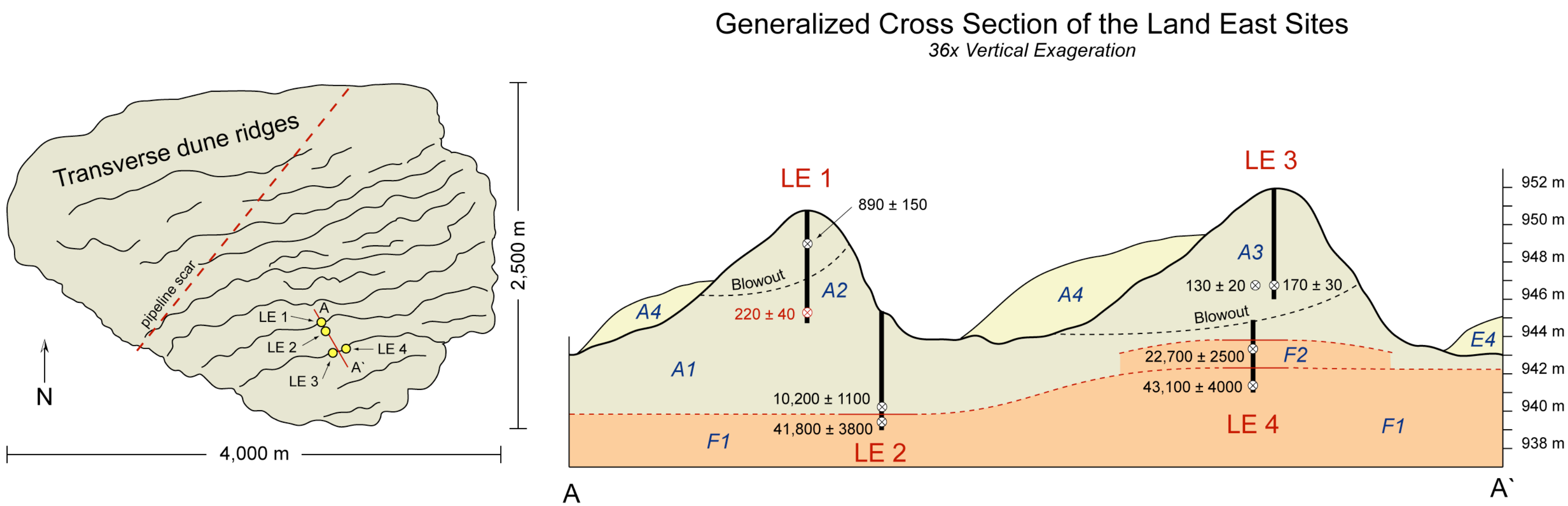

Figure 4.26. Stratigraphic profiles of sites within the Land East sample area. Ages are presented in years before 2010.

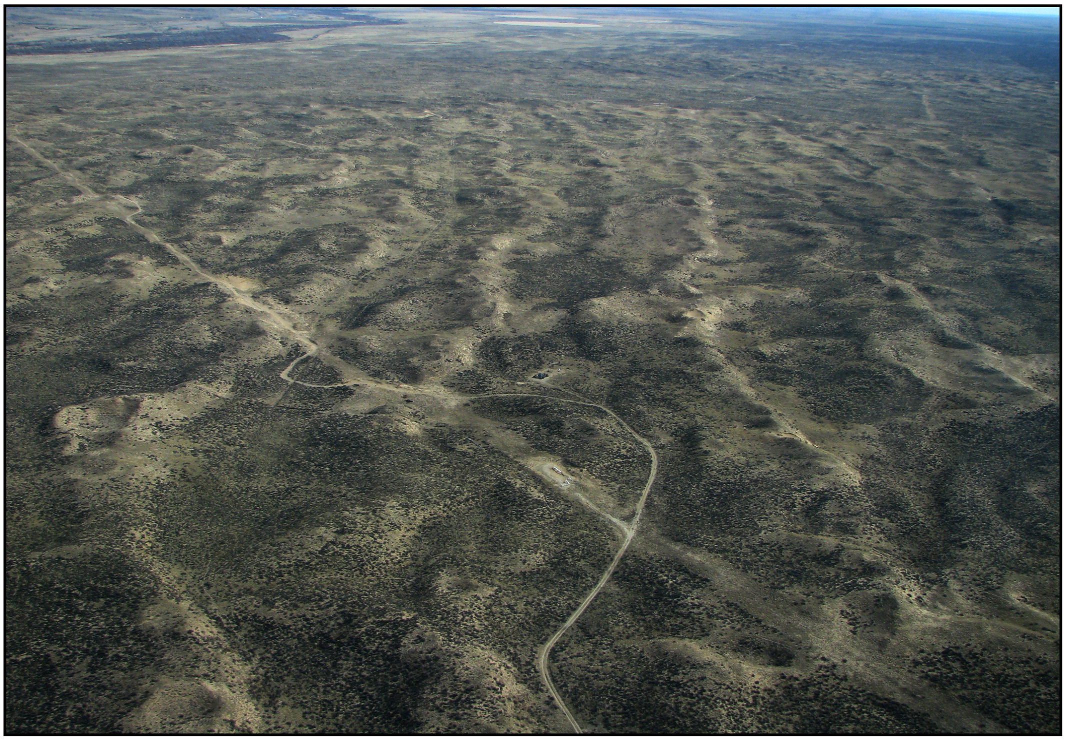

Figure 4.27. Aerial view looking east of the transverse dunes of the Land East (LE) sites. Steep slip faces on the transverse dunes indicate a south to southeasterly direction of dune migration (i.e., northerly winds).

Figure 4.28. Aerial view looking northeast at a northeasterly trending parabolic dune, which butts up against a southeasterly trending transverse dune. A two-wheel road is located in the upper left for scale. Local dune relief in this area is ~18 m.

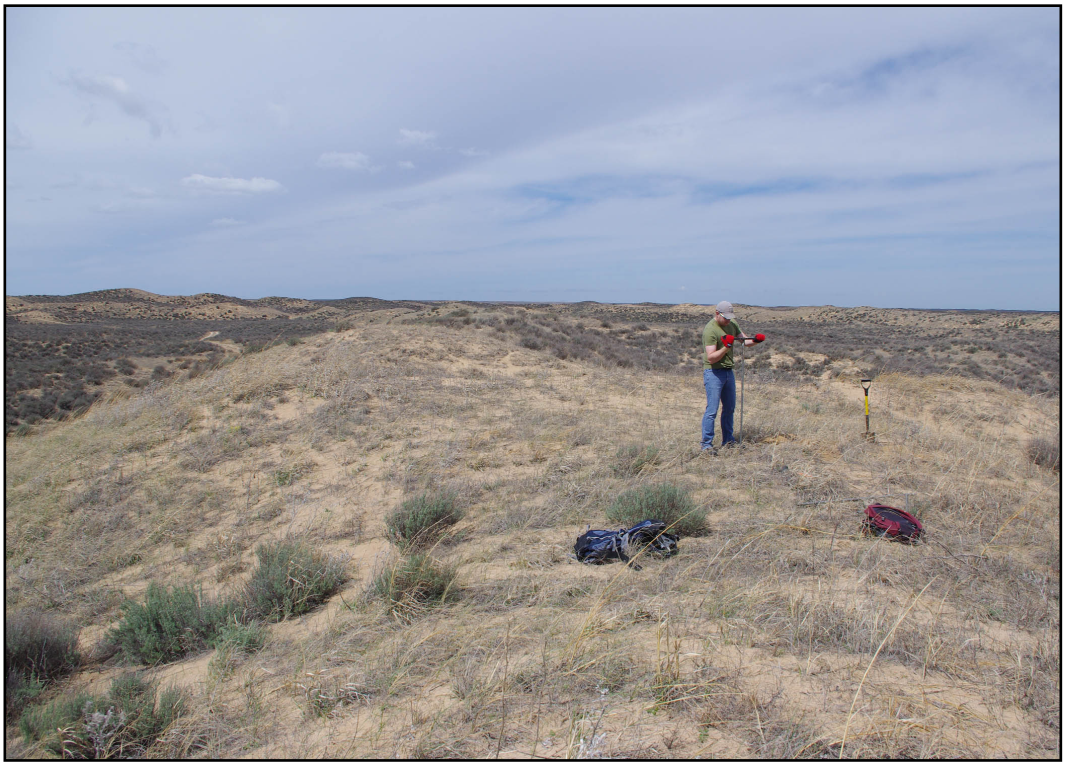

Figure 4.29. View to the west of AFH auger sampling at the LE 1 site (dune crest).

Figure 4.30. Sampling at the LE 2 site adjacent to an oilfield collection pipeline.

Figure 4.31. Looking southwest to the LE 3 site, on the dune crest (arrow).

Figure 4.32. View south of AFH auguring in the blowout at the LE 4 site.

In addition to sampling this transverse dune ridge from the crest, a bucket auger was used to sample the dune horizontally from the lower face of the blowout at the LE 4 site (Fig. 4.4B). The horizontal auger hole extended ~5 m into the dune where an OSL sample (LE 5-1) was collected, at approximately the same x-y-z location as that of sample LE 3-1. The LE 5-1 sample yielded an age of 130 ± 20 years ago, which lies within a 1σ error of LE 3-1 (170 ± 30 years ago).

4.3.2.11. P5 Ranch sites (GM 1–2)

The GM sites (Fig. 4.33) are located on the P5 Ranch, south of Kendall, Kansas, in a section of the dune field where younger episodes of dune activation have overprinted older dune field activity. An auger was used to explore stratigraphy to a depth of 3.5 m at the GM 1 site, the wing of a southeast-facing parabolic dune (Fig. 4.34). Other than a weakly developed surface soil, no changes in dune stratigraphy were noted, and an OSL sample collected at 3.3 m dated to 520 ± 50 (GM 1-1) years ago. Auguring was also used to sample in the corresponding dune swale ~35 m north and 10 m lower in elevation from the GM 1 dune crest site (Fig. 4.35). Dune swale stratigraphy consisted of a moderately well developed surface soil in aeolian sediment ~4.3 m thick. Abundant concentrations of $CaCO_3$ observed in the surface soil continued throughout the aeolian sediment to the base of the auger hole at 4.3 m deep. An OSL sample (GM 1-2) collected from the bottom of the auger hole and yielded an age of 10,300 ± 900 years ago.

The GM 2 site, located in a gravel quarry just south of the Arkansas River ~5 km north of the GM 1 site, consisted of a profile ~1.5 m high created in the eastern quarry face. A thin layer of alluvial silt and clay was documented overlying gravelly alluvium, and an OSL sample collected within the alluvium yielded an age of 1990 ± 160 (GM 2-1) years ago.

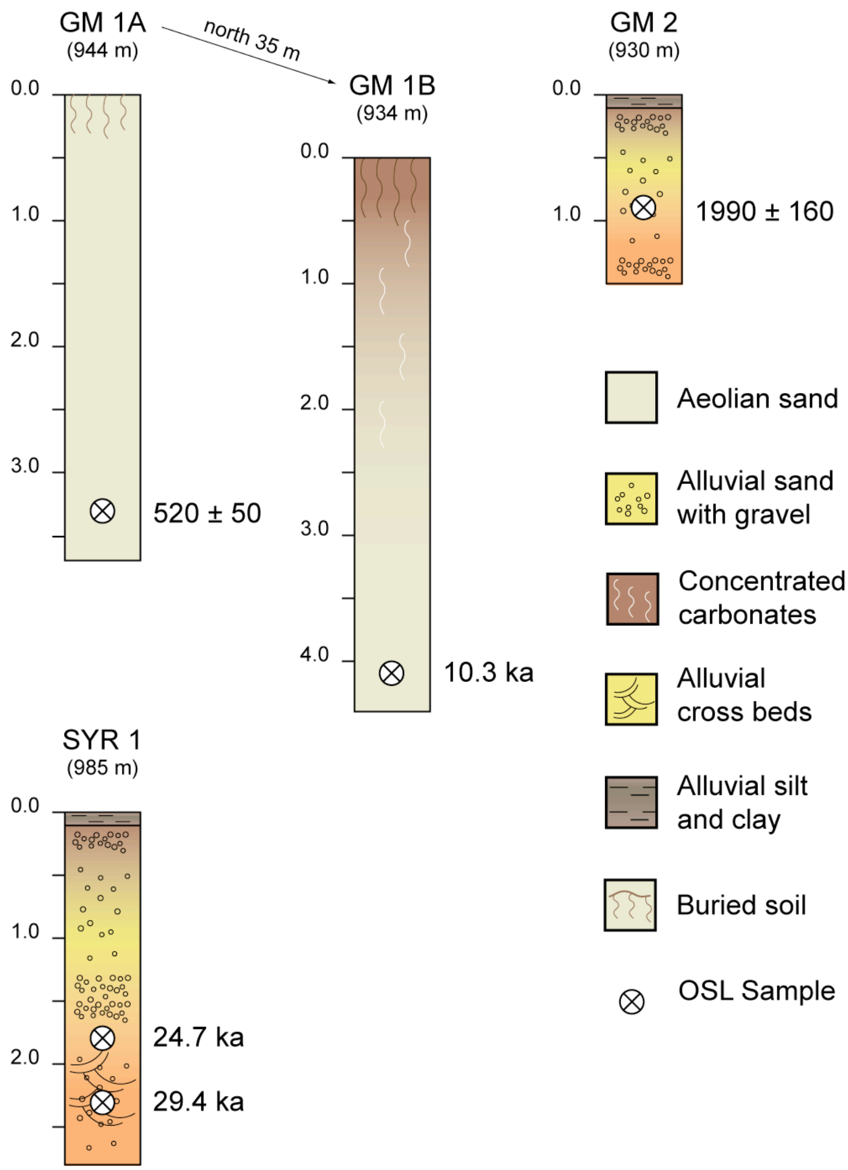

Figure 4.33. Stratigraphic profiles of the GM 1–2 sites and the SYR 1 site. Ages are presented in years or ka years before 2010.

Figure 4.34. View north from the crest of a south-trending parabolic dune. The GM 1 site is located on the western arm of this dune (arrow).

Figure 4.35. View north from the crest of a south-trending parabolic dune. The GM 2 site is located in the basin of this dune (arrow).

4.3.2.12. Syracuse Feedlot (SYF 1)

The SYF site (Fig. 4.33), located within a gravel quarry on the northern edge of the Arkansas River valley ~2 km east of Syracuse, Kansas, exposes ~10 m of alluvial sand and gravel (Fig. 3.36). A profile was constructed in the northern face of the quarry beginning at a thin layer of alluvial silt and clay, which transitioned to sand and gravel exposed to the base of the quarry. Two OSL samples collected from the base of the profile at 1.8 (SYR 1-1) and 2.3 m (SYR 1-2) yielded ages of 24,700 ± 2500 and 29,400 ± 3200, respectively.

Figure 4.36. Profile excavated in the northern face of the abandoned quarry near the Syracuse Feed Lot.

4.3.2.13. Tarbet Quarry (TB 1)

Two sand and gravel quarries are located directly south of Syracuse, Kansas, within the modern Arkansas River floodplain, one east and one west of State Highway 27

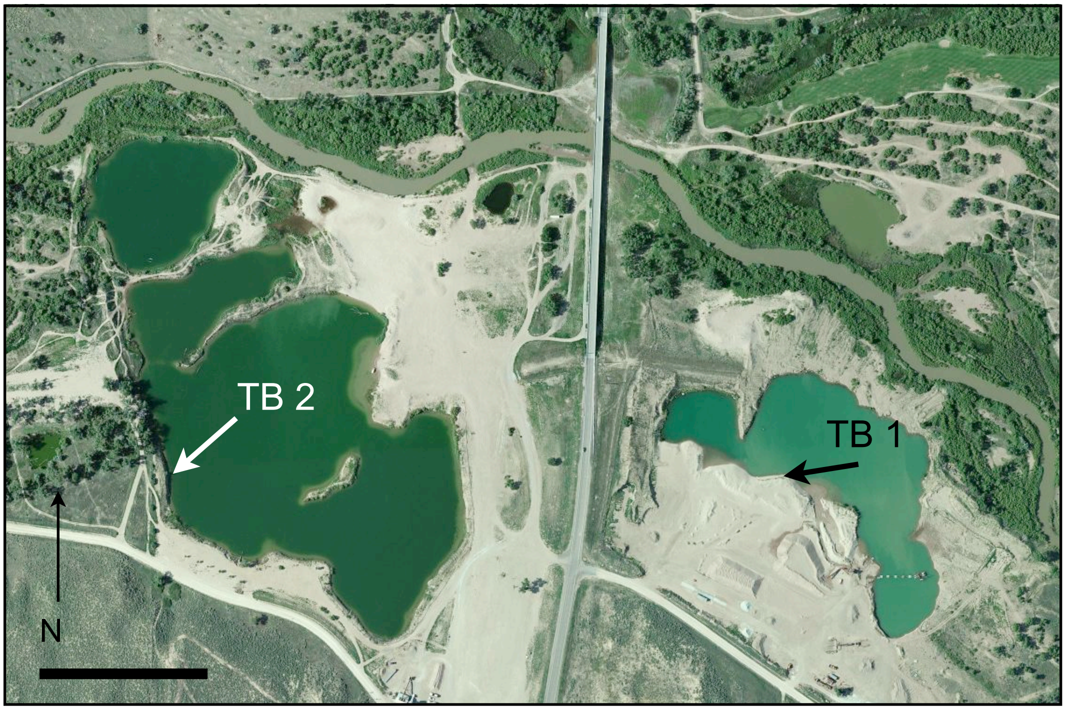

Figure 4.37. 2011 NAIP imagery of the Tarbet Quarry sites (arrows) showing proximity to the Arkansas River channel during a time of high stream discharge—typically, the channel is dry most of the year in this part of the Arkansas River valley, south of Syracuse, Kansas. Scale bar = ~250 m.

(Figs. 4.2. 4.39). Each of these quarries are proximal to the Arkansas River, resulting in a high water table, which has filled the quarries (Fig. 4.37). A 2 m high profile was created in the north-facing bank of the the eastern quarry (TB 1). The profile consisted of overburden from a nearby tailings pile ~30 cm thick, underlain by ~30 cm of laminated silts and clays, ~20 cm of planar-laminated sand, and a thin (~5 cm) layer of alluvial clay. At ~80 cm deep, the profile transitions to coarse sand with flaser laminations underlain by cross-bedded sandy gravel, which continues to the bottom of the profile. An OSL sample (TB 1-1) collected within the sandy alluvium providing an age of 190 ± 20 years ago.

A profile was created in the the western quarry (TB 2), exposing markedly different stratigraphy from that of the eastern quarry (Fig. 4.38). Stratigraphy consisted of ~70 cm of aeolian sand capped by a weak surface soil (~30 cm-thick), ~30 cm of alluvial silts and clays, underlain by zones of lamented and planar-bedded sands, and cross-bedded sands and gravels, which could be traced to the base of the quarry face (water table). Two OSL samples collected from TB 2, one in aeolian sediment (TB 2-1) and another in alluvium (TB 2-2), producing ages of 500 ± 50 and 1160 ± 110 years ago, respectively.

Figure 4.38. Upper part of the ~2 m profile constructed at the western Tarbet Quarry (TB 2 site).

4.3.2.14. Syracuse ORV Park sites (SD 1–4)

The SD sites are located within the 600 ha Syracuse Off-road Vehicle (ORV) Park (currently the *Syracuse Sand Dunes Park*), south of Syracuse, Kansas (Figs. 4.2, 4.39). Dunes in this park are transverse ridges, which have been highly modified by younger generations of dune activity and, more recently, by anthropogenic (ORV) activity. Also, the park management is actively removing vegetation in park, which has

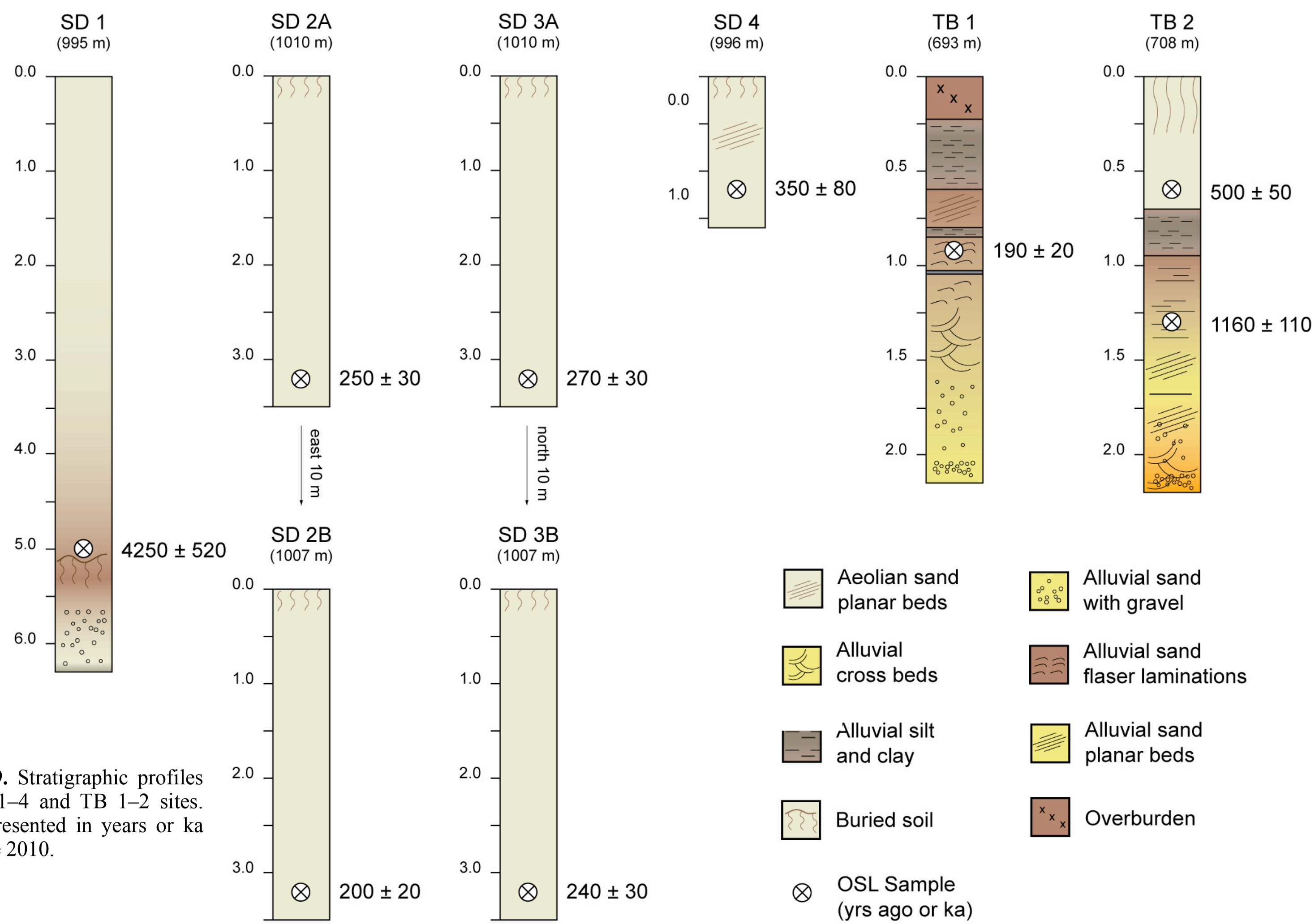

Figure 4.39. Stratigraphic profiles of the SD 1–4 and TB 1–2 sites. Ages are presented in years or ka years before 2010.

subsequently promoted dune activity (Fig. 4.40). While park fees provide much needed income to a region of Kansas with little economic activity, management has had difficulty containing dune activity within the boundary of the park in that active dunes are now encroaching on neighboring ranch land, making it unsuitable to grazing (John Armstrong, 2010: *personal communication*). Though the anthropogenic activity in this area may be ecologically detrimental, conditions are ideal for sampling—four sites within the park were sampled for stratigraphy and chronological control.

Site SD 1, located in the basin of a large blowout ~5 m below the crest of the adjacent dune in the southeast corner of the ORV park (Fig. 4.41), was augured to determine dune stratigraphy beneath the blowout and to collect OSL samples. Aeolian sand occurred to a depth of ~5 m where a probable buried soil was encountered. The buried soil, estimated to be only ~20–30 cm thick, was underlain by aeolian sand to a depth of ~5.75 m, where the sand abruptly changed to gravelly alluvium, which continued to the bottom of the auger hole at ~5.75 m depth. An OSL sample (SD 1-1) collected at the SD 1 site in aeolian sand above the buried soil at 5 m dated 4250 ± 520 years ago.

The SD 2 site, located in the southwest corner of the ORV park on the crest of the parks's tallest dune, was augured from the crest to a depth of 3.5 m (SD 2A), and another 3.5 m deep auger hole was created downslope ~3 m and east ~10 m of the dune crest. No visible changes in dune stratigraphy were noted in either of these auger holes. Two OSL samples, each collected from a depth of 3.4 m (SD 2-1, SD 2-2), yielded ages of 250 ± 30 and 200 ± 20 years ago. The SD 3 site is similar to the SD 2 site in that it is comprised of two auger holes sampled from the crest and downslope of a tall dune in the western ORV park. Like the SD 2 site, no visible changes in stratigraphy were noted, and two OSL samples obtained from each of these auger holes at 3.2 m (SD 3-1, SD 3-2) produced ages of 270 ± 30 and 240 ± 30 years ago.

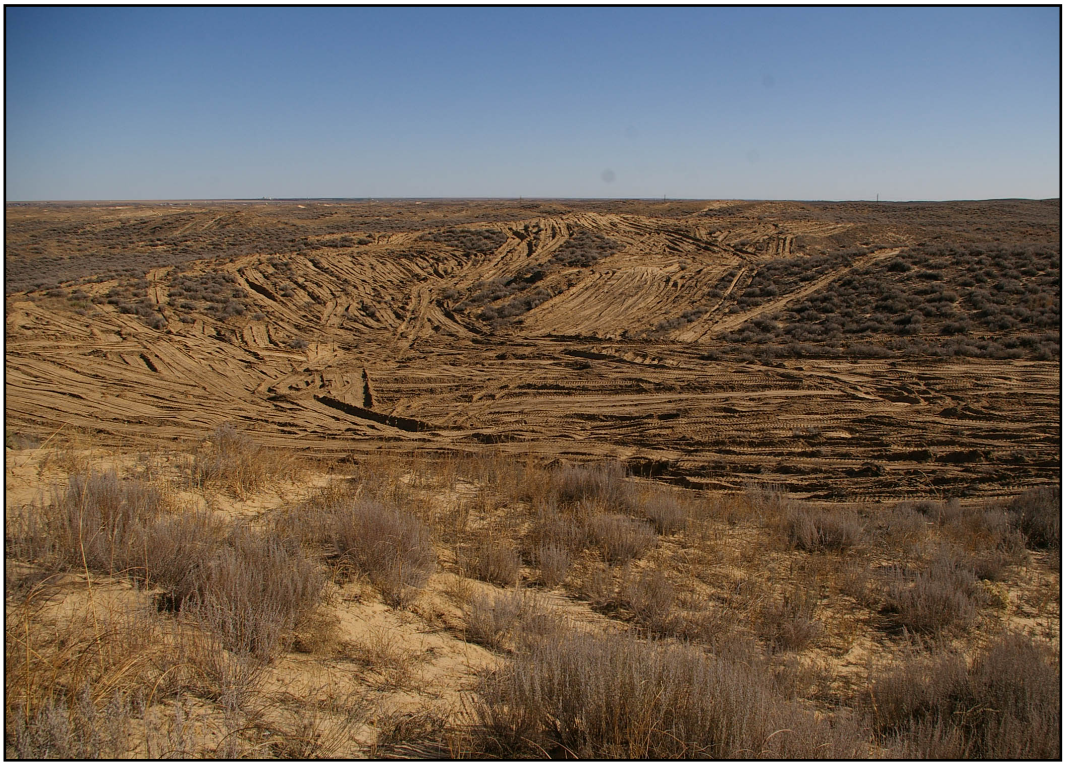

Figure 4.40. A bulldozer has been used to remove vegetation in an areas of the Syracuse ORV Park, which has promoted dune activity.

Figure 4.41. The SD 1 site with bucket auger extension rod and handle protruding from the auger hole.

The fourth site in the ORV park, a small exposure along an ORV trail, consisted of a profile that exposed ~1.4 m of aeolian sand with a thin (<10 cm) buried soil at ~80 cm (Fig. 4.42). This buried soil could be traced along the trail for ~75 m in each direction, indicating a fairly horizontal and consistent buried surface. An OSL sample (SD 4-1) collected below this buried soil at 1.2 m dated to 350 ± 80 years ago.

Figure 4.42. The SD 4 site, a low road cut exposing a buried soil (arrows) along a park trail.

4.3.2.15. Wharton Ranch sites (WH 1–5)

About 5 km south of Coolidge, Kansas, at the Wharton Ranch, is a large isolated blowout measuring ~1200 m north to south and ~600 m east to west (Figs. 4.3G, 4.43). Much of the blowout surface is covered by a "hard pan" surface, which was created through a combination of four factors: 1) input of fine-grain aeolian deposition; 2) fine-grain fluvial slope-wash from the edges of the blowout (which contain fine-grained

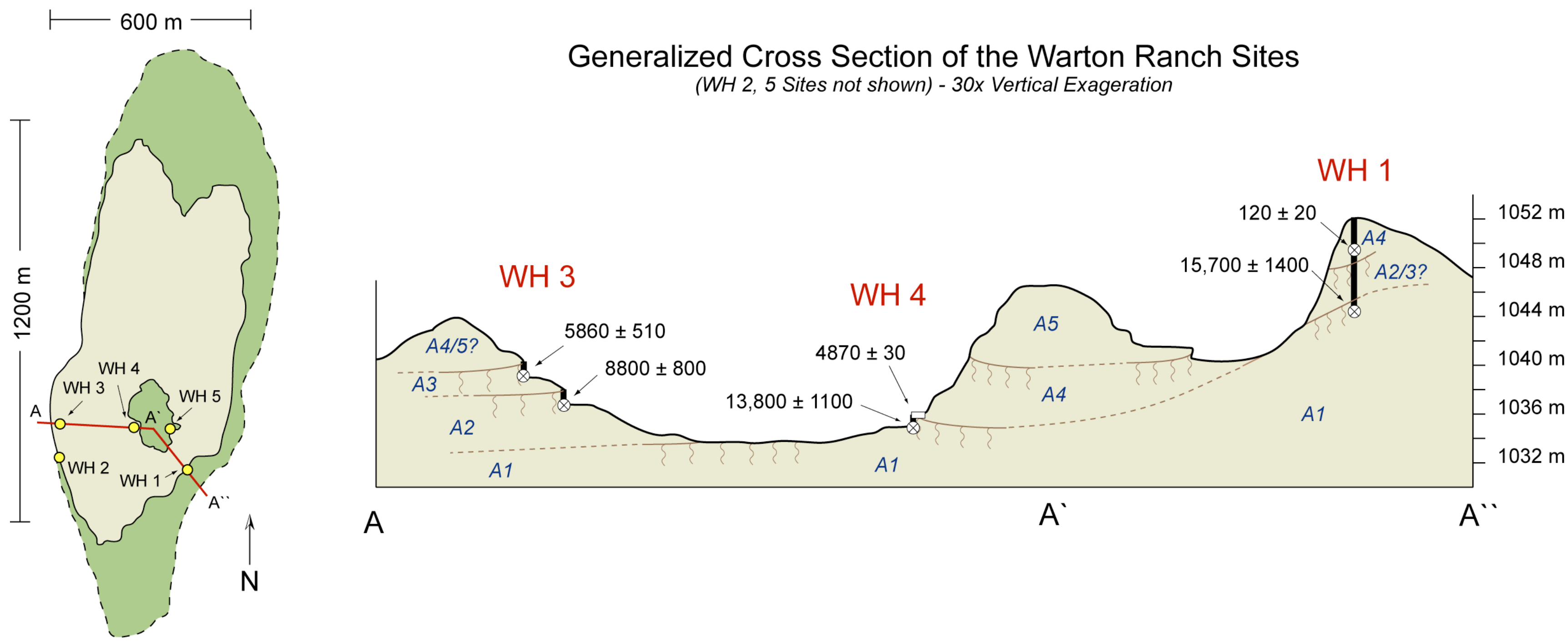

Figure 4.43. Stratigraphic profiles and generalized cross section of the WH sites. The darker shading around the active blowout is the part of the blowout, which is only partially stabilized by sparse vegetation. Ages are presented in years before 2010.

Figure 4.44. The WH 1 site. Layers of fine-grained, darker material can be seen outcropping in the area.

layers); 3) slight cementation by $CaCO_3$;; and 4) modest vegetation cover, which acts as both a source of organic material and the catalyst for trapping fine-grained sediment (see discussion in section 4.4.2.3). The blowout has been actively migrating, albeit slowly, since at least the 1970s towards the north during the summer when prevailing winds are dominantly from the south, and then back to the south during the winter when prevailing winds are dominantly from the north (Rusty Wharton, 2010: *personal communication*). In the center of the blowout, towards the southern end is a stabilized remnant of aeolian sand, which appears to have survived while the rest of the blowout has deflated. Five sample localities were established within this blowout (WH 1–5) in order to create a transect extending from the southeastern edge of the feature, through the middle aeolian remnant, and then to the western edge (Fig. 4.43).

Auguring was used to explore the stratigraphy and collect OSL samples at the WH 1 site, located at the southeastern crest of the blowout (Fig. 4.44). Aeolian sediment was documented throughout the auger hole; however, the stratigraphy was divided into three distinctive units: an upper 2.5 m of aeolian sediment with little to no change in stratigraphy, and two disparate, thin, fining-upward packages of aeolian sand, each about ~50 cm thick. These packages transitioned from very fine sand/coarse silt, to medium sand, and then to coarse sand. The fine-grained component of these packages is interpreted to be the same fine-grained material exposed within the blowout south of WH 1 (Fig. 4.43), possibly representing periods of dune field stability. A second auger hole was augured ~10 m northwest and ~3.5 m downslope of the first hole. No visible change in stratigraphy was noted until ~3 m, where the aeolian sediment transitioned rapidly to fine-grained material ~20 cm-thick interpreted as a weak buried soil, beneath which more aeolian sand was documented. Two OSL samples collected from the WH 1 site, one within the second fining upward package (WH 1-1) and another below the lowest buried soil (WH 1-2), dated 120 ± 20 and 15,700 ± 1400 years ago, respectively.

The WH 2 site, located ~500 m due west of the WH 1 site on the opposite blowout edge (Fig. 4.43), is characterized by ~60–80 cm thick beds of aeolian sand packaged between thin layers (<10 cm) of darker, fine-grained material, considered to be buried surfaces similar to the hard pan that covers much of the blowout today. A profile ~1 m deep was created to expose the contact between aeolian sand and a buried surface, and an OSL sample (WH 2-1) collected at the base of the profile dated 12,600 ±1100 years ago.

The WH 3 site is located ~100 m north of the WH 2 site, also along the western edge of the blowout (Fig. 4.43). Similar to WH 2, this site is characterized by beds of aeolian sediment (1–1.5 m thick) between buried surfaces, and, although the packages at WH 2 and WH 3 are similar, they could not be traced between the two sites. At the WH 3 site, two 1 m deep profiles were created one above another, each exposing a contact between two different aeolian beds and buried surfaces (Fig. 4.45). Optically stimulated luminescence samples (WH 3-1, 3-2) were collected in aeolian sand from the base of

Figure 4.45. The upper of the two 1 m deep profiles at the WH 3 site. The fine-grained contact is visible separating beds of aeolian sand.

Figure 4.46. Profile within the bench at the WH 4 site.

each of these profiles, yielding ages of 5860 ± 510 and 8800 ± 800 years ago.

The remaining site along the cross-sectional transect of this blowout is WH 4, located on the western edge of the central aeolian remnant (Fig. 4.43). This site is similar to those along the western flank of the blowout in that it exposes multiple packages of aeolian sediment and buried surfaces. Aeolian sand above a 25-cm thick, fine-grained surface had been partially deflated, leaving a small bench capped with a fine-grained, darker sediment 25 cm thick, suggesting it may represent a period of dune stabilization and soil development. A 1.2 m profile was created below this bench exposing the buried soil, which contained weak blocky structure, underlain by horizontally laminated aeolian sand. An OSL sample collected from the bottom of the profile at 1 m (WH 4–1) dated 13,800 ± 1100 years ago, and an AMS ^{14}C age collected from upper 5 cm of the Ab soil (WH 4–1R) yielded an age of 4830 ± 25 calibrated years before present (4240 ± 30 ^{14}C yrs BP).

The WH 5 site, located on the eastern edge of the isolated aeolian remnant (Fig. 4.43), was not sampled for chronological control but is characterized by ~40 cm of aeolian sand with well-expressed lamellae (Fig. 4.47), suggesting active pedogenesis (Rawling, 2000; Johnson et al., 2008). If the formation of lamellae is related to sub-surface water flow as suggested by Johnson et al. (2008, p. 489), then the three-dimensional appearance of the lamellae at the WH 5 site indicates both lateral and vertical movement of water in the subsurface sediments at the site.

4.4. Discussion

4.4.1. Overview of chronological data

OSL data collected in this study are well behaved, producing reliable ages with errors ≤ ~10%. A single inversion occurred at the LE 1 site, where an age of 890 ± 150 years ago collected at 3.2 m (LE 1-1) overlies a younger age of 220 ± 40 years ago from 6.3 m (LE 1-2). The younger of these ages has been excluded because the sample was

Figure 4.47. The WH 5 site, showing vertical and horizontal clay lamellae.

apparently contaminated by surface sediment resulting in a erroneously young age and a 20% error. Contamination may have occurred because the auger bit had broken during extraction of the sample; this condition allowed the bucket to collect fall-in from near-surface sediment.

Additionally, several samples collected in this study (n=26) have not yet been fully analyzed, and, although these undated samples would contribute to the chronology, they would likely only serve to reinforce the periods of aeolian activity already recognized in the chronology developed with the existing 53 samples because they were collected from similar stratigraphic positions in dunes with the same morphologies as those already providing age data. Additionally, when the ages from this study (n=53) are compiled with those from Forman et al. (2008) (n=21), a total of 74 OSL ages and six AMS ^{14}C ages are available to create a chronology of aeolian and fluvial activity. In comparison, this study still provides the second highest number of OSL ages used to create a chronology from a single Great Plains dune field—second only to Miao et al. (2007a) who reported a chronology of aeolian activity from the Nebraska Sand Hills using 95 OSL ages.

4.4.2. Expanded geomorphological interpretations

4.4.2.1. The Land East sites

The Land East sites are found within a region of the ARD dominated by older transverse dunes, which have been overprinted with younger generations of parabolic dunes (Fig. 4.26). Chronological data from this area suggest that aeolian sediment was deposited ~10,000 years ago on top at least two Pleistocene alluvial units (Fig. 4.26: F1 & F2). Initial dune formation resulted in the development of large transverse dunes (Fig. 4.26: A1). The location of these dunes south of the Arkansas River, as well as steep dune slip-faces facing the southeast, indicates that these transverse dunes formed under north-northwest winds.

Following their initial formation, these transverse dunes stabilized, only to reactivate again during periods of drought conditions during the Holocene. Unlike the activity that occurred during initial formation, that during the Holocene was more sediment starved, which resulted in only portions of the transverse dunes being destabilized, in turn creating localized blowouts from which new generations of parabolic dunes formed. For the most part, younger generations of dunes reflect southerly paleowinds, though some parabolic dunes within interdune areas reflect westerly paleowinds (Fig. 4.28).

In some locations, younger dunes remained within the interdune areas of the original transverse dunes, but, in others, dunes were reworked and incorporated into the original transverse dune ridges (Fig. 4.26: A2 & A3). Evidence of isolated dune activity is evidenced by the formation of new transverse dunes and recorded in historical images of the area from the 1930's Dust Bowl (Fig. 4.48A), which indicates that some transverse dunes began to migrate back towards the river. While this may have been the case, all evidence from this study still suggests that the initial core of the original transverse dunes, which formed under predominately northerly winds, appears to remain preserved, and, based on the morphology of dune slip faces in the area of the LE sites, not all south-trending transverse ridges reorganized into north-trending ridges during the 1930s.

Finally, isolated blowouts, which may have remained active since the 1950s, continue to deflate, resulting in the deposition of dune sediments north of transverse ridges (Fig. 4.26: A4). These blowouts are more visible when less precipitation leads to drought-like conditions that inhibit the growth of vegetation and promote destabilization of these blowouts. For example, blowouts were extremely active in 2003, following 2002, a year which in this area of western Kansas experienced ~180 mm less

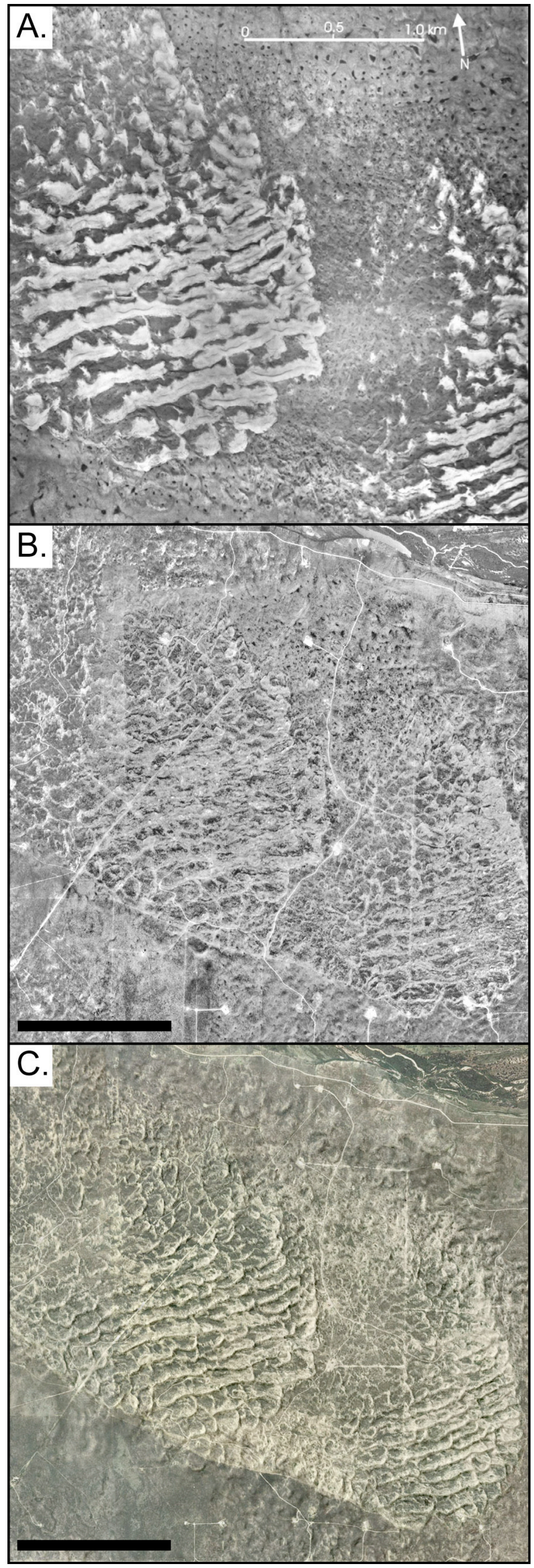

Figure 4.48. Aerial images of the dune field near the Land East sites. Images taken: A) 1936; B) 1991; C) 2003. Scale bar in each image = ~1 km.

precipitation than average (Fig. 4.48C) (HPRCC, 2012). Similarly, aerial photographs from the summer of 1991 show that this area of the ARD remained severely scarred (void of vegetation) following widespread droughts during the later part of the 1980s (Fig. 4.48B).

4.4.2.2. The Wharton Ranch sites

The Wharton Ranch (Fig. 4.43), located in the far western region of the ARD, presents a unique opportunity to articulate a drastically different story of dune activity than that of the Land East sites. The Wharton Ranch sites are associated with a large blowout, but the area around this blowout is devoid of definable dune formations. Instead, the area is characterized by rolling topography, interpreted to be primarily a sand sheet deposit. Well-defined dunes occur only ~2 km east of the Wharton blowout; however, these dunes were dated and interpreted by Forman et al. (2008) to have formed only very recently (i.e., ~300–200 years ago), while most chronological evidence from the Wharton Ranch suggest early- to middle-Holocene aeolian activity.

The fairly ubiquitous aeolian sand and buried surfaces found at the Wharton Ranch blowout, together with a lack of any cross-bedding within buried aeolian bedding, suggests, that this part of the dune field experienced limited dune building episodes.

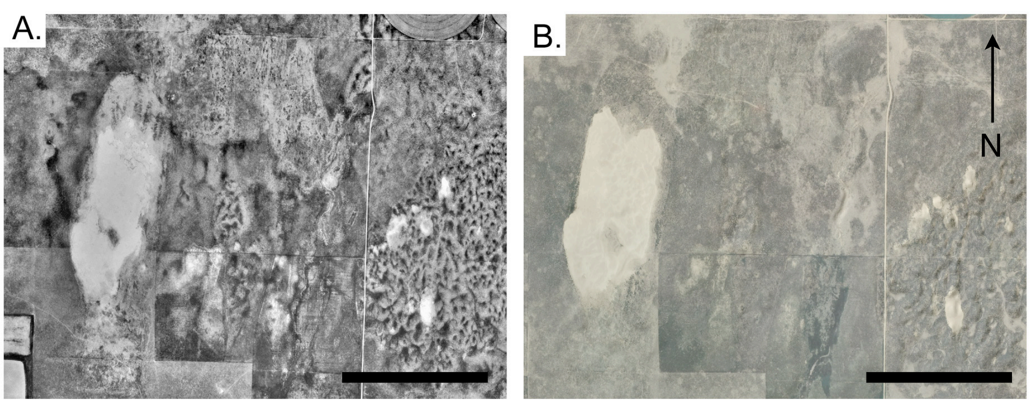

Figure 4.49. Aerial images of the Wharton Ranch blowout. Images taken: A) 1991; B) 2006. Scale bar in each image = ~1 km.

More likely, the area was built of episodic sand sheet deposits, which resulted in the deposition of thin layers of aeolian sediment, that, if stabilized, could have formed the buried surfaces found in the area.

The blowout observed today is the result of only late-Holocene deflation (i.e., within the last 2000 years), which likely began as a small blowout, and, due to strong seasonal changes in wind, progressively expanded while retaining most of the active sand within the feature. Two factors support this interpretation: 1) no OSL ages from this study support aeolian activity after marked stability at 4400 years ago, except for one age of ~190 years ago, and 2) there are no dunes north or south of the blowout, which, considering late-Holocene wind regimes, would have resulted if a large amount of sediment had been deflated from the blowout. What is known for certain is that this blowout has been active since at least the 1970s (Rusty Wharton, 2010: *personal communication*). Additionally, aerial images from 1991 (Fig. 4.49A) and 2006 (Fig. 4.49B) show little change occurring in the blowout boundary, other than perhaps widening. Within the last six years (2006–present), the blowout has continued to expand as it has in the past (compare Fig. 4.49 to Fig. 4.3G: taken in 2010).

4.4.3. Chronology of Arkansas River valley alluvium

OSL ages from alluvial sediments within the ARD document alluvial deposition beginning prior to 55,000 years ago and continuing up until only ~190 years ago. Though supported only by a limited number of ages, a significant period of alluvial deposition appears to have occurred ~30,000–24,000 years ago. Forman et al. (2008) also documented the deposition of a high terrace (~3–5 m above the Arkansas River) ~30,000 years ago, which is probably equivalent to alluvial fills documented in this study. At the Syracuse Feedlot site, for example, two alluvial ages (SYF 1-1: 24,700 ± 2500; SYF 1-2: 29,400 ± 3200) are ~5 m above the modern Arkansas River. In addition, an OSL age of 27,600 ± 2700 (BP 5-2) years ago was obtained from alluvial sediment ~5 m above the modern Arkansas River in the far eastern edge of the dune field. Though Forman et al. (2008) considered this the high terrace, this study has identified older terraces that are higher in elevation, such as that which underlies the Land East sites ~8 m above the modern Arkansas River. OSL ages from this terrace suggest deposition ~43,000–42,000 years ago, which correlates well with timing of alluvial deposition in the Smoky Hill river valley ~350 km east (Hanson et al., 2010). An OSL age of >55,000 years ago was also collected from alluvium underlying the PR 4 site on the far eastern margin of the dune field, though this terrace was only ~5 m above the modern Arkansas River.

Ages of alluvial deposition between ~30,000–24,000 years ago are roughly coincident with a transitional period in the loess stratigraphy of Kansas and Nebraska; specifically, the transition from a relatively stable period of pedogenesis in the Gilman Canyon Formation (Soil 2; ~30,000–28,000 years ago; Johnson et al. 2007) to the more active period of Peoria Loess deposition (Johnson et al., 2007; Aleinikoff et al., 2008; Muhs et al., 2008). Ages of alluvial deposits in the Arkansas River valley ~30,000–24,000 years ago also date between the last Bull Lake glacial advance and the Pinedale glacial advance in the upper Arkansas River basin in the Colorado Rocky Mountains (Madole, 1986; Briner, 2009; Pierce, 2011).

OSL ages from this study also document another significant period of alluvial deposition on a lower terrace between ~22,000–13,000 years ago. Forman et al. (2008) recorded similar alluvial ages, though they suggested that deposition had ended prior to ~16,000 years ago. Johnson (1991) and Arbogast and Johnson (1998) also documented alluvial deposition in the Great Bend Sand Prairie prior to ~16,000 years ago and prior to ~23,000 years ago 250 km downstream near Wichita, Kansas (Rogers and Martin, 1985; Jaumann et al., 1985). Alluvial activity ~22,000–13,000 years ago is also concurrent with earliest dune activity recorded in the ARD (see section 4.4.3), and deposition of alluvium at this time may have led to the initial formation of the ARD. Forman et al. (2008) hypothesized that initial aeolian deposition in the ARD at this time may not reflect regional aridity, rather a change in sediment availability as the Arkansas River transitioned from a single channel system to the braided stream present today. Evidence of paleochannels that meandered across the river valley are visible in several places within the modern Arkansas River valley (Fig. 4.50). These paleochannel features were described by Johnson and Dort (1988) as late-Pleistocene features partially covered by Holocene aeolian sands.

Figure 4.50. 2011 NAIP imagery of the paleochannels that meandered across the Arkansas River Valley. These features are found ~10 west of Syracuse, Kansas. Scale bar = ~500 m.

Briner (2009) and Young et al. (2011) used cosmogenic ^{10}Be exposure dating to derive a chronology of the Pinedale glaciation and subsequent deglaciation in the upper Arkansas River basin of the Colorado Rocky Mountains. Not only do these studies place the maximum limits of the Pinedale advance at ~22,000 years ago, but they suggest that the Clear Creek glacier (Clear Creek Valley) and Pine Creek glacier (Pine Creek Valley) may have acted as ice dams, which collapsed ~19,000 years ago. A secondary Pinedale advance and ice dam collapses were dated between ~16,000 and 13,000 years ago. The drainage of these glacially dammed lakes was sufficient to deposit large boulder trains (~20–10 m in diameter) downstream ~5–8 km (McCalpin, 2010). The rapid drainage of glacially dammed lakes in the upper Arkansas River basin at this time would have sent mass quantities of water and finer grained sediment (i.e., sand and gravel) down the Arkansas River, essentially shocking the river system, causing it to change from a single channel systems to a wide, braided channel stream as Forman et al. (2008) suggested. Whether or not this change was caused directly by an outburst flood, clearly there is correlation between the collapse of the Pinedale glaciers in the upper Arkansas River basin at the end of the Pleistocene and changes realized in downstream channel morphology of the Arkansas River valley.

Finally, three OSL ages from alluvial sediments in the ARD show alluvium being deposited during the Holocene ~2000 (1990 ±160; GM 2-1), ~1100 (1160 ± 110: TB 1-1) and ~200 (190 ± 20: TB 2-2) years ago, and these ages provide evidence for the deposition of alluvium throughout the late Holocene. These relatively young samples were collected within 500 m of the present day Arkansas River, and their young ages are not surprising considering that historical accounts for Garden City, Kansas in the 1870s recount the width of the Arkansas River being nearly 1 km wide (http://www.ksda.gov/dwr/content/371/cid/1670).

4.4.4. Arkansas River dunes aeolian activity

Dune activity documented from the 35 study sites within the ARD spans the latest Pleistocene, beginning during the Older Dryas (~16,000 years ago) through the Younger Dryas (~13,000–12,000 years ago), and into the Holocene (<12,000 years ago) (Fig. 4.51). The oldest evidence for aeolian deposition is that ~16,000 years ago (15,700 ± 1400: WH 1-2) associated with the Wharton Ranch blowout at the very southern edge

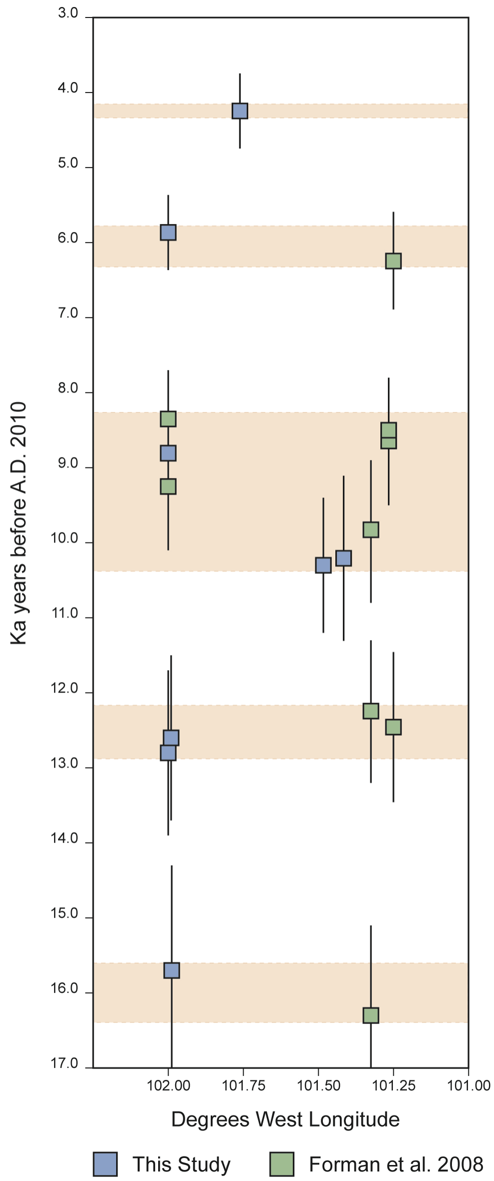

Figure 4.51. OSL ages from aeolian dunes reported in this study and Forman et al. (2008), arrayed by degrees west longitude, from 17,000 to 3000 years ago (before A.D. 2010). Horizontal shaded bars indicate probability peaks of aeolian depositional events reported by Forman et al. (2008).

of the dune field. Additional ages from the Wharton Ranch blowout also document aeolian activity ~14,000–13,000 years ago (12,600 ± 1100: WH 2-1; 13,800 ± 1100: WH 4-1). Two OSL age from south-trending dunes have basal ages of ~10,000 years ago, which were collected directly above underlying alluvium (10,300 ± 900: LE 1-2; 10,200 ± 1100: GM 2-1). Forman et al. (2008) also dated dune activity in the ARD between ~16,000–12,000 years ago in the area of the Land East sites (reference Fig. 4.28).

Collectively, these ages suggest that initial dune field formation occurred between ~16,000–10,000 years ago in concert with the morphology changes in the Arkansas River, which would have provided the sandy sediment needed to form a dune field. The transverse dune morphology of many places in the ARD, particularly those west of Garden City, indicates also that abundant sediment was available for deposition during this time.

Though initial dune activity has been suggested ~16,000–10,000 years ago, a single AMS ^{14}C sample, which dated to 23,130 ± 600 cal yrs BP (19,430 ± 200 ^{14}C yrs BP: FO 1-2R), was collected from a well developed buried soil within dune deposit south of Dodge City, Kansas. This age is significantly older than the OSL ages collected from dunes throughout the rest of the ARD. Evidence for aeolian activity at this time is available within the ARD, though it is limited. For example, Simonett (1960) documented Peoria Loess (~24,000–17,000 years ago) south of the ARD south of Garden City, Kansas, and an additional AMS ^{14}C age from this study, collected from a buried soil within a loess deposit south of Dodge City, Kansas, dated to 22,870 ± 480 cal yrs BP (19,130 ± 150 ^{14}C yrs BP: FO 1-1R). Considering the evidence for loess deposition prior to 16,000 years ago, the coarse grain component of the loess may have been deposited south of the river as well.

Additional OSL ages from the ARD document limited early- to middle-Holocene aeolian activity ~8800, 5900, and 4300 years ago. Two of these periods of aeolian activity are recorded at the Wharton Ranch blowout, where beds of aeolian sediment with ages of 8800 ± 800 (WH 3-2) and 5860 ± 510 (WH 3-1) years ago are constrained by buried soils. Stratigraphy at this site suggests that aeolian activity must have ceased long enough for vegetation to re-establish and a weakly developed soil to form. The period of dune activity at ~4300 years ago was documented at the Syracuse ORV Park from a deep auger hole in the blowout of a large transverse dune (Fig. 4.39). This age is suggested to represent a discrete period of aeolian activity because an AMS ^{14}C age from a buried soil at the Wharton Ranch site dated to 4830 ± 25 cal yrs BP (4240 ± 30 14C yrs BP: WH 4-1R), indicating that the dune field was stable prior to ~4300 years ago.

Forman et al. (2008) also reported middle-Holocene aeolian activity, though their OSL results documented only episodic activity ~9800–6300 years ago. Both ages from this study and those from Forman et al. (2008) correlate with ages of loess deposition documented south of Garden City, Kansas (Olson et al., 1997). When combining the ages from this study and those of Forman et al. (2008), it appears that aeolian activity within the ARD was fairly continuous from ~10,500–8,000 years ago (Fig. 4.51); however, buried soils within the dune field suggest that this period of activity was punctuated by brief periods of stability.

Though evidence for middle-Holocene activity exists, this activity is extremely limited and only documented in the far western parts of the ARD (i.e., west of Garden City, Kansas). A lack of widespread aeolian activity at this time may be the result of several factors including a sampling bias. Another probable factor, however, is that younger episodes of aeolian activity in the ARD were sufficient to have erased much of the middle-Holocene aeolian record from the dune field. A similar situation was noted in the Hutchinson dunes ~200 km downstream east of the ARD (Halfen et al., 2012).

The potential to overprint middle-Holocene dune activity is clearly illustrated in the abundance of OSL samples which document late-Holocene dune activity (Fig. 4.52). OSL samples from Forman et al (2008) and this study collectively indicate dune activation after ~1000 years ago, widespread dune activity between ~600–190 years ago, and during historic times. A slight peak in aeolian activity may have occurred after ~400 years ago, but it most definitely occurred between ~270 and ~190 years ago. OSL ages from this latest peak in dune activity indicate that large quantities of dune sediment were migrating at this time, given the ~7 m of sand accumulating within a short period at two sites at the Syracuse ORV Park (western dune field) and ~5 m of sand at the Pyle Ranch (eastern dune field).

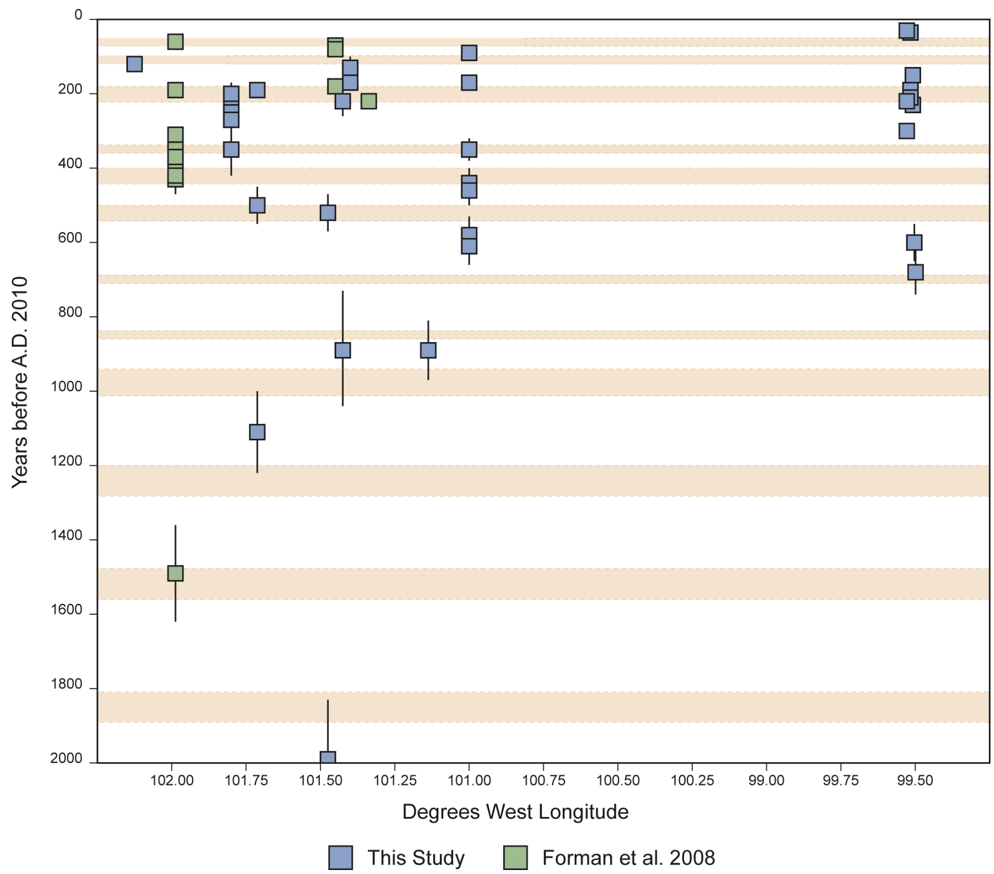

Figure 4.52. OSL ages from aeolian dunes reported in this study and Forman et al. (2008), arrayed by degrees west longitude, from 2000 years ago to present (A.D. 2010). Horizontal bars indicate defined periods of drought identified from Palmer Drought Severity Index records for the past 2000 years for southwestern Kansas (modified from Cook and Krusic, 2004; Forman et al., 2008).

After a peak in dune field activity between ~270–190 years ago, relative stability must have returned to the region, because the pre-1930's soil is found throughout most parts of the dune field. At the same time, however, isolated dune activity is documented between ~190 years ago and the 1930s, suggesting that the dune field, if stable, may have had isolated pockets of dune activity or isolated blowouts, similar to the landscape of today. Additionally, the upper (~190 years ago) and lower (~80 years ago) limiting ages of the pre-1930's soils suggest that it formed in 100 years or less.

Lastly, OSL ages from the ARD document activity during droughts of the 1930s and 1950s. Not only is dune activity supported with OSL ages at this time, but also with historical records, such as newspaper accounts, early aerial photographs (e.g., Fig. 4.47A), and first hand communication from landowners.

In summary, aeolian activity in the ARD has been documented to have first occurred ~16,000–10,000 years ago and is speculated to have been the result of a rapid influx in sediment associated with the changing morphology of the Arkansas River. By ~10,000 years ago, the major alluvial events of the Arkansas River had ended, and episodic dune activity continued until at least ~4300 years ago, though evidence for significant activity at this time is limited. The dune field reactivated again in the late Holocene after ~1000 and ~600 years ago and continued to remain active, though again episodically, until ~190 years ago. Finally, a brief period of stability occurred after ~190 years ago as evidence by the presence of a pre-1930s soil found throughout the dune field, followed by historical reactivation during droughts of the 1930s and 1950s.

4.4.5. Regional chronological correlation of dune field activity

Multiple ages from aeolian sediments at sites spread throughout the dune field suggest that the ARD first formed during the latest Pleistocene (i.e., after 16,000 years ago) into the early Holocene (i.e., prior to 10,000 years ago). Aeolian activity during this time was significant and resulted in the deposition of a thick sand sheet (i.e., the Wharton Ranch site) and large south-trending transverse (i.e., Land East, Syracuse ORV park sites) and parabolic dunes (i.e., P5 Ranch sites). Many Great Plains dune fields first formed during the Pleistocene or early Holocene, though significant variability exists in the exact timing of their initial formation. For example, Holliday (2001) documented dune activity in the Southern High Plains as early as ~25,000 years ago, whereas, Mason et al. (2011) reported the earliest episode of dune activity ~17,000–16,000 years ago in the Nebraska Sand Hills. Mason et al. (2011) acknowledged, however, that the Sand Hills were probably somewhat older. In Canada, timing of initial dune field activity between ~16,000 and ~14,000 years ago has been linked to the retreating Laurentide Ice Sheet (e.g., Wolfe et al., 2004; Wolfe et al., 2007b). Dune activity is also noted in the Fort Morgan dunes of Colorado between ~16,000 and ~11,000 years ago (e.g., Forman and Maat, 1990; Madole, 1994; 1995).

The timing of initial dune activity in the ARD most closely related to activity recorded in the Nebraska Sand Hills and the Fort Morgan dunes. Dune morphology from all three dune fields suggest formation under north-northwesterly winds (e.g., Madole, 1995; Schmeisser et al., 2010; Mason et al., 2011). All three dune fields are associated with large alluvial rivers with headwaters in glaciated regions of the Rocky Mountains. Accordingly, the collapse of Pinedale glaciers likely led to major changes in fluvial activity that was expressed downstream in many Great Plains dune fields, specifically the ARD, Fort Morgan dunes, and Nebraska Sand Hills. Any aeolian activity associated with upstream glacial events in the Nebraska Sand Hills must have been subsequent to earlier aeolian activity because the Platte River lies south of the Sand Hills and does not match the wind vectors necessary to form the large barchanoid ridges of the Sand Hills, i.e., the primary sediment source of the Sand Hills is not the Platte River (Muhs, 2004; Mason et al., 2011).

Episodic early- to middle-Holocene dune activity ~10,000–4300 years ago also occurred in the in the ARD. Within this time interval (5700 years), most dune fields throughout the Great Plains also document some record of aeolian activity (see review in Chapter 2). Numerous Great Plains paleoclimate studies record omnipresent drought conditions during the Holocene Climatic Optimum (~9000–5000 years ago: Baker, 2000; Fritz et al., 2001; Grimm et al., 2011), and, as such, several authors have attributed episodic dune field activity during the early and middle Holocene to these droughts (e.g., Miao et al., 2007a; Halfen et al., 2010). Evidence for widespread aeolian activity during the early and middle Holocene is also recorded within the region loess deposits of the Great Plains (Aleinikoff et al., 2008; Muhs et al., 2008).

Within the ARD, and, generally throughout many Great Plains dune fields, ages of dune activity from the early and middle Holocene are very limited: many dune field show activity at this time, but activity is only supported with a handful of ages from each dune field. Limited ages at this time may indicate only minor dune field activity or a sampling or preservation bias of aeolian sediment this age. In the ARD, evidence suggests that limited age data are a result of a preservation bias considering the extreme late-Holocene dune activity, which likely erased the majority of dune activation ages from the early Holocene. A similar condition is present in the Hutchinson dunes of Kansas where aeolian activity within the last ~600 years has erased essentially the entire chronological record of Holocene dune activity.

Dune activity was also documented in the ARD after ~4300 years ago, although, once again, timing of dune activity at this time is limited to only a few isolated ages, and no ages provide any evidence for when this dune activity ended. Dune activity following ~4300 years ago been reported in the Brandon Sand Hills of Manitoba (Wolfe et al., 2000; 2002a), the Casper dunes (Halfen et al., 2010), the Nebraska Sand Hills and Duncan dunes (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007a; Hanson et al., 2009), the Fort Morgan dunes (Clarke and Rendell, 2003), and in the Muleshoe dunes of the Southern High Plains (Holliday, 2001). Chronologies from these studies may provide an estimate of when dune activity in the ARD ~4300 years ago ended. For example, Miao et al. (2007a) documented dune activity in the Nebraska Sand hills at this time to have ended by ~2300 years ago. Similarly, Wolfe et al., (2000) also documented dune stability in the Brandon Sand Hills by ~2300 years ago. Most important to this study, however, is the stability and soil development noted in the Great Bend Sand Prairie ~2300 years ago (Arbogast, 1996; Arbogast and Johnson, 1998). Because the ARD and the Great Bend Sand Prairie are in close proximity, under similar climatic regimes, and influenced by the same fluvial system, aeolian activity in both may have ended by ~2300 years ago. Again, limited ages of dune activity between ~4300 and 1000 years may be the result of the preservation bias created when late-Holocene dune activity reactivated most of the dune field. The sole OSL age indicating dune activity within the ARD after ~4300 years ago could, however, be erroneous or more likely represent only isolated dune field activity.

Finally, the ARD contain a record of widespread dune field activity during the late Holocene, beginning about ~1500 years ago as documented by Forman et al. (2008). Dune activity was also documented in the western Nebraska Sand Hills (Goble et al., 2004; Forman et al., 2005) and in the Great Bend Sand Prairie prior to ~1400 years ago (Arbogast, 1996; Arbogast and Johnson, 1998). Gridded Palmer Drought Severity Index (PDSI) reconstructions from eastern Colorado document two periods of drought ~1700 and ~1500 years ago, which may correlate to dune activity at this time (Fig. 4.52). The same PDSI index from grid sites in Kansas cannot, however, confirm this drought because the tree-ring records do not extend back far enough (reference gird point 162, 163; Cook and Krusic, 2004).

The next significant period of aeolian activity in the ARD is that which occurred ~900 years ago, a time of significant dune activity documented throughout the Great Plains, which many researchers have attributed to climate changes associated with the Medieval Climatic Anomaly (MCA) (Halfen et al., 2012 and references therein). Dune activity between ~1000–800 years ago is noted in almost every Great Plains dune field, though the exact timing of this activity appears to fluctuate. For example, Miao et al. (2007a) described MCA dune activity in the Nebraska Sand Hills as not ending until ~700 years ago. Conversely, Halfen et al. (2012) documented that MCA dune activity in the Hutchinson dunes had ended by ~900 years ago.

Documenting MCA dune activity in the ARD is an important finding of this study because, up until now, the ARD was the only major dune field on the Great Plains to not record this activity. Although Forman et al. (2008) attributed the apparent gap of aeolian dune activity during this time to an incomplete reproduction of the stratigraphic record, a lack of dune activity in the ARD has led researchers to question the spatial boundaries of megadroughts at this time (e.g., Lepper and Scott, 2005; Hanson et al., 2009; 2010; Werner et al., 2011; Halfen et al., 2012). Ages from this study indicate, however, dune activity following the MCA, which together with other dune studies suggests that megadroughts at this time were widespread throughout the Great Plains.

Multiple OSL ages from this study and from Forman et al. (2008), document near continuous aeolian activity from ~600 years ago to ~190 years ago. Aeolian activity within the last 600 years has also been documented in far western areas of the Nebraska Sand Hills (Forman et al., 2005; Mason et al., 2011), the Wray and Fort Morgan dunes of Colorado dunes (Muhs et al., 1997b; Clarke and Rendell, 2003), dunes in Oklahoma (Werner et al., 2011), and the Hutchinson dunes of Kansas (Halfen et al., 2012). Significant aeolian activity also occurred in the Southern High Plains within the last ~700 years. For example, the Muleshoe dunes were active after ~700 and ~500 years ago, and the Seminole sand sheet was active between ~400 and ~300 years ago (Holliday, 2001). The Muleshoe dunes and Seminole sand sheet, as well as the Lea-Yoakum and Andrews dunes of Texas, were all active within the last 200 years (Holliday, 2001). Halfen et al. (2012) speculated that dune activity within the last ~600 years was linked to regional megadroughts associated with the Little Ice Age, and that megadroughts during this time, unlike those of the MCA, were constrained to the southern and western Great Plains.

Historical dune field activity on the Great Plains is widely documented in early newspaper stories and settlement records (e.g., personal journals and memoirs) of the region, which date back to the later part of the 19th century. References to these documents are widespread in archives of Great Plains historical societies, particularly those which document dune activity during the 1930's Dust Bowl (e.g., http://www.kancoll.org/khq/; http://www.weru.ksu.edu/new_weru/). Activity is also observed in aerial photographs and recounted first hand from land owners who lived through these events and the newly released NOVA documentary titled "The Dust Bowl" by Ken Burns (http://video.pbs.org/program/dust-bowl/)

4.5. Conclusions

Alluvial and aeolian sediments of the ARD in southwestern Kansas have a rich and complex depositional history that begins ~55,000 during the late Pleistocene and continues up through historical times. Prior to aeolian deposition, thick sequences of alluvial sediments were deposited in numerous packages dated ~43,000–42,000 years ago, ~30,000–24,000 years ago, and between ~22,000–13,000 years ago. Approximately 16,000 years ago, the morphology of the Arkansas River changed dramatically from a single meandering channel system to a broad braided channel system. These changes may have been triggered by massive glacial outburst floods in the upper Arkansas River basin, though linking the timing of a downstream fluvial change to these events is difficult since errors associated with these events are on the orders of centuries. Nevertheless, fluvial changes in the Arkansas River ~16,000 years ago are mostly likely related to collapse of the Pinedale glaciers in the upper Arkansas River valley at the end of the Pleistocene.

Aeolian activity in the ARD began ~16,000 years ago with the formation of the sand sheet and dune field south of the Arkansas River, which included the formation of large networks of south-trending transverse dunes. Evidence from the dune field, alluvial record, and upstream glacial record collectivity suggest that initial dune formation in the ARD was the result of a significant shift in fluvial activity. OSL ages support aeolian activity between ~16,000 years ago up until ~4300 years ago, although this activity was episodic as evidenced by the presence of buried soil within the ARD that indicate stability prior to ~9000, 6000, and 5000 years ago. The most significant episode of aeolian activity occurred in the ARD within the last 2000 years after ~1500 and ~900 years ago, and within the past 600 years. Aeolian activity within the last 600 years is the most widely documented, suggesting widespread mobilization of the ARD at this time. A brief hiatus of dune activity occurred about 190 years ago until it resumed again during historical droughts of the 20th century.

Chapter 5

MIS 3 DUNE FIELD DEVELOPMENT IN THE CENTRAL GREAT PLAINS (THE GREAT PLAINS' OLDEST DUNE FIELD)

5.1. Introduction

Within the last four decades, considerable research has been undertaken to determine the geomorphic history and paleoclimatic importance of Great Plains aeolian dune fields (see review in Chapter 2). At the forefront of these studies have been those that aim to reconstruct the paleoclimatic history of the region using dune field activity as a proxy for intense, geographically extensive megadroughts. Multiple studies demonstrate that dune fields throughout the Great Plains reactivated multiple times during the Holocene in response to these droughts, in particular those associated with major climatic events, such as the middle-Holocene Climatic Optimum (e.g., Miao et al., 2007; Halfen et al., 2010), the Medieval Climatic Anomaly (Hanson et al., 2009; 2010), and the Little Ice Age (Forman et al., 2005; Forman et al., 2008; Halfen et al., 2012). Little attention has been given, however, to reconstructing the timing of Great Plains dune field activity during the Pleistocene primarily because: 1) most Great Plains dune fields are Holocene features lacking records of Pleistocene activity, in part because some of the region was covered by the Laurentide Ice Sheet (Fig. 5.1); 2) most Great Plains dune field aeolian records are preferentially biased towards the late Holocene because younger episodes of dune activity typically erase older records (e.g., Halfen et al., 2012); and 3) only major (> 100 km^2) dune fields of the Great Plains have been accurately mapped, which in turn has left smaller dune fields, which may contain a Pleistocene record of activity, relatively unnoticed and consequently understudied.

In 2011, one of these smaller dune fields was mapped in the eastern Kansas River valley, Kansas (Fig. 5.2) (Rockel et al., 2010). Though the Kansas River dunes (KRD)

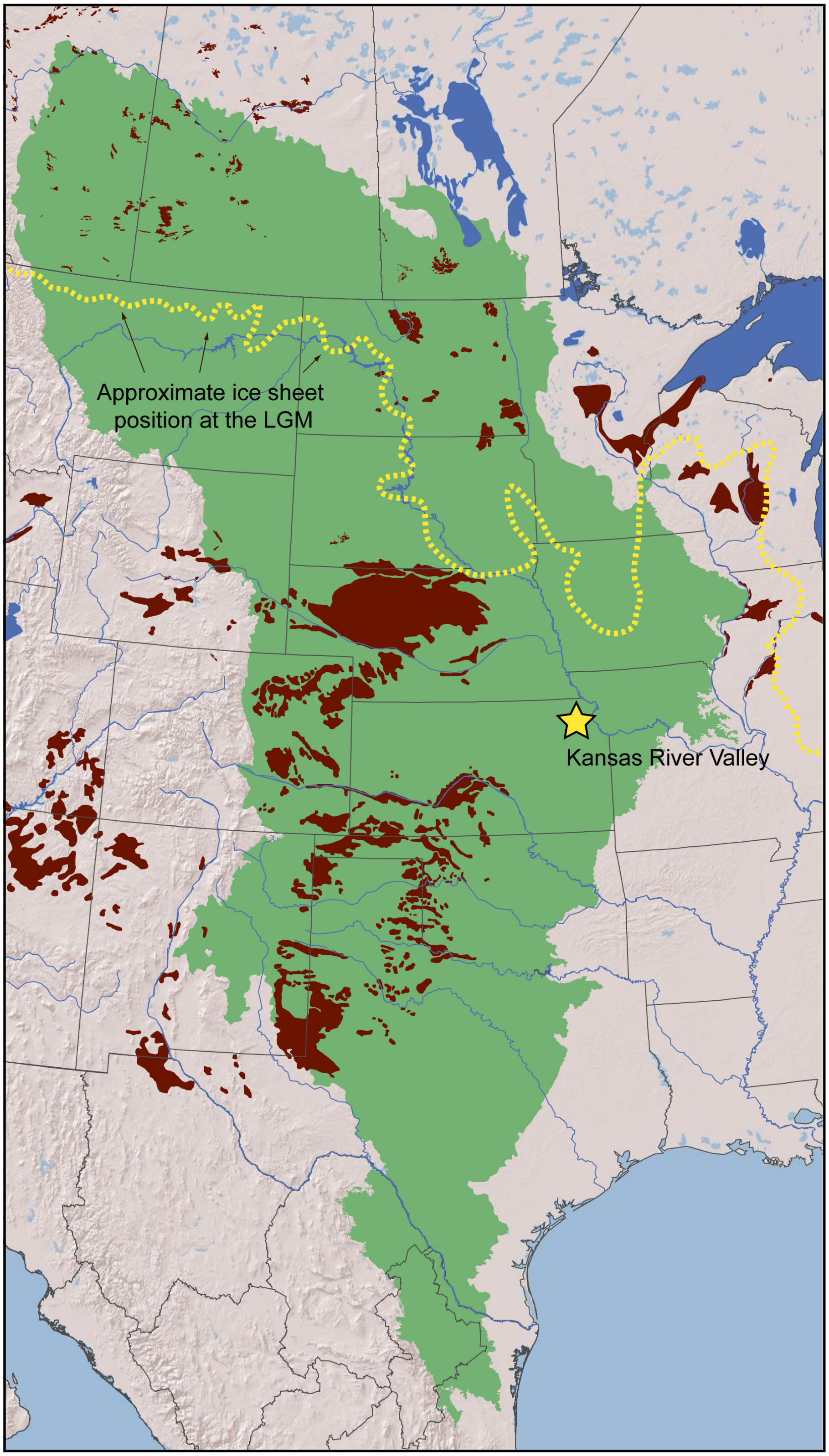

Figure 5.1. Aeolian dune fields of the North American Great Plains, including the approximate location of the Kansas River valley (modified from Wolfe et al., 2009). Approximate position of the LGM ice sheet after Muhs et al. (2008).

had been recognized in earlier literature (Davis and Carlson, 1952; Fader, 1974; Sorenson et al., 1985), the timing of their formation was unknown but postulated to have occurred sometime between ~650 ka and ~10 ka. Constraining the temporal patterns of dune formation in the KRD will better help assess the paleoclimatic conditions of the eastern Great Plains during the Pleistocene. Towards that end, this study presents a new optically stimulated luminescence (OSL) chronology for the KRD, which places their formation during Marine Isotope Stage (MIS) 3 and discusses the paleoclimatic significance of dune field activity in the central Great Plains during MIS 3, which at present is poorly understood.

MIS 3 is characterized from ice-core data as a relatively mild period within the last glacial between ~60 ka and ~24 ka (NGRIP Member, 2004; Van Meetbeeck et al., 2009). This period was marked with abrupt transitions between cold stadials to mild interstadials, designated Dansgaard-Oeschger (DO) events, which have been documented in ice-core and marine records extending from the Holocene, where they are expressed as Bond events (Bond et al., 1997; 2001) to as early as 200 ka (Dansgaard et al., 1993; Bond et al., 1995). Most evidence for DO events suggests they are the result of fresh water releases into the North Atlantic (e.g., Dansgaard et al., 1993; Bond and Lotti, R., 1995), though other causal mechanisms, such as sea ice feedbacks and changes to the tropical ocean have also been suggested (Clement and Peterson, 2008). Another climatic feature of MIS 3 are Heinrich events (Heinrich, 1988; Bond et al., 1992; 1993), which were massive discharges of ice rafted debris to the North Atlantic during the late Pleistocene. Multiple Heinrich events (H) have been documented during MIS 3, including H6 (~60 ka), H5 (~45 ka), H4 (~38 ka), and H3 (~31 ka) (Hemming, 2004).

Though a significant record of MIS 3 climate change exists in ice-core and marine records, those from continental records are still widely undocumented, especially within the North America Great Plains. In general, North American climate during MIS 3 was highly variable and strongly seasonal, reflecting mostly changes associated with DO

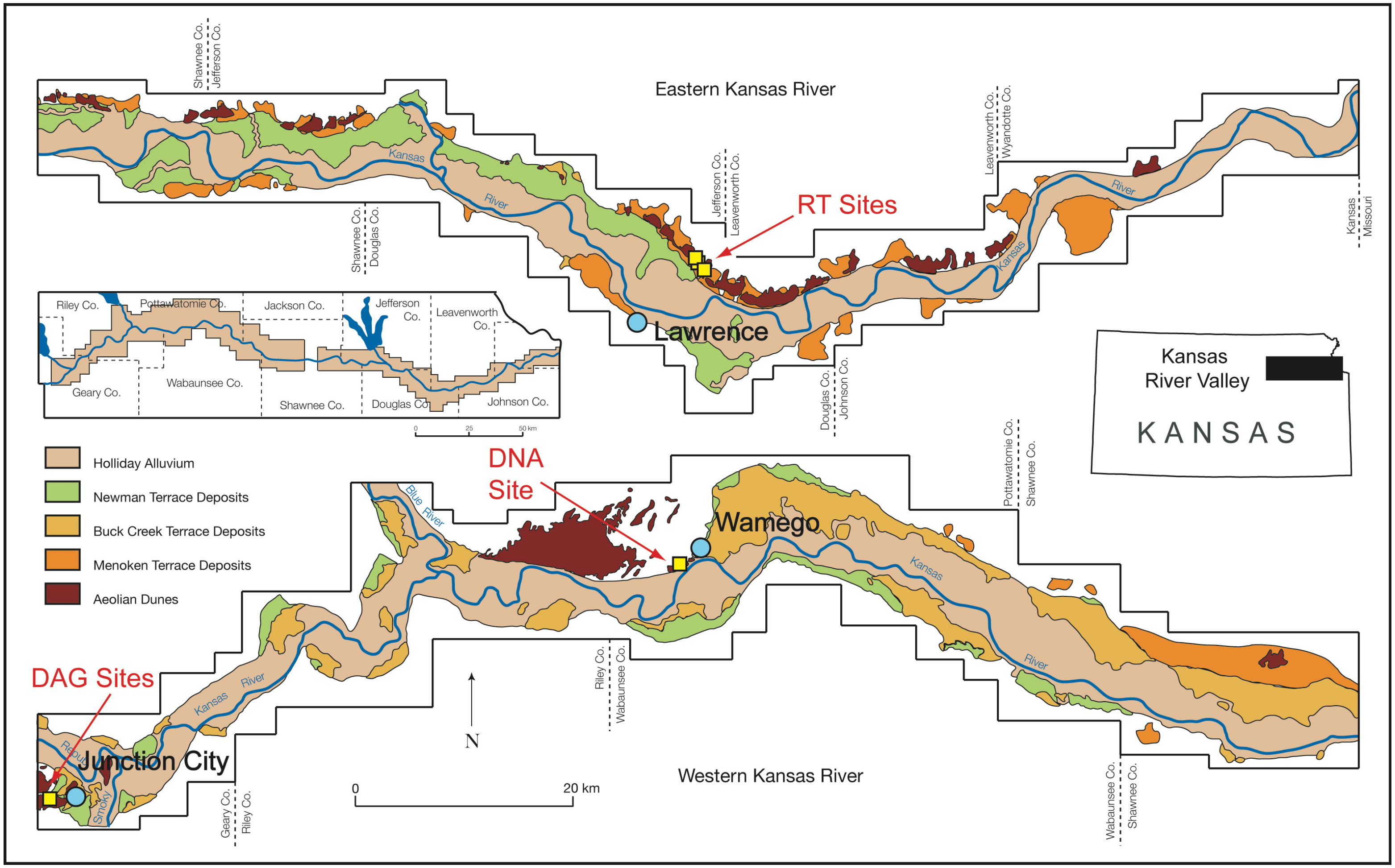

Figure 5.2. Surficial geology of the Kansas River valley after Sorenson et al. (1985). Sample sites discussed in this study are identified with yellow boxes.

events and peaks in summer insolation (Markgraf et al., 2000; Van Meetbeeck et al., 2009). North American continental records are limited for MIS 3 (Voelker et al., 2002), and, of those available, few exist for the central Great Plains, the closest being the record of loess stratigraphy. Three late-Quaternary loess units recognized in the central Great Plains are, oldest to youngest, the Gilman Canyon Formation, Peoria Loess, and Bignell Loess, all of which have been dated with luminescence and radiocarbon techniques to between ~40–25 ka, ~25–12 ka, and < ~10 ka, respectively (Muhs et al., 2008). Ages from the Gilman Canyon Formation, the oldest of these units (~40–25 ka), place its deposition during MIS 3 (Maat and Johnson, 1996; Johnson et al., 2007).

Johnson et al. (2007), using multiple proxies, concluded that Gilman Canyon Formation loess began to accumulate under high atmospheric dust loads prior to 40 ka, after which dust loads decreased allowing for the slow (< 1 mm per year) accumulation of loess and concurrent pedogenesis. Carbon isotopic values ($\delta^{13}C$) from buried soils within the Gilman Canyon Formation (Soil 3) reflect dominance by C_4 grasses, indicating warmer growing seasons. High dust loads resumed ~29 ka, and $\delta^{13}C$ values decreased, indicating the dominance of cool-season C_3 vegetation. A similar shift to warmer conditions with less loess accumulation and greater soil formation also occurred ~26 ka. Johnson et al. (2007) noted that the height of soil formation (~35 ka) was coincident with a peak in summer (July) isolation, which would have resulted in temperatures equal to or exceeding those of today.

Other paleoclimatic records available for MIS 3 on the Great Plains are the $\delta^{18}O$ and $\delta^{13}C$ records from speleothems collected within Reed's Cave, South Dakota, which documented a period of cooling ~50–45 ka, followed by warmer condition ~35 ka (Serefiddin et al., 2004). A similar transition from a cool to warmer climate was also documented in Crevice Cave, southeastern Missouri occurring ~55 ka and ~37 ka, respectively (Dorale et al., 1998).

5.2. Geological setting

Isolated pockets of aeolian dunes mantle a high terrace within the Kansas River valley in northeastern Kansas (Fig. 5.2). The surficial geology of the river valley, which includes four Quaternary alluvial terraces and aeolian dunes, was originally mapped by Davis and Carlson (1952) and most recently remapped by Rockel et al. (2010). From oldest to youngest, the terraces within the valley are the Menoken, Buck Creek, Newman, and Holliday. The Menoken Terrace is an outwash terrace atop glacial till, found only on the northern edge of the River Valley, ~25–30 m above the floodplain. The terrace is a feature of the Kansas glacial event, which most evidence suggests occurred prior to ~700 ka (Aber, 1991; Gosse et al., 1997). About 15 m below the Menoken is the Buck Creek Terrace, which consists of silt and clay fill and in some places is thinly mantled by loess (Davis and Carlson, 1952). A suite of radiocarbon ages, including one from loess on top the Buck Creek Terrace, and several collected within the terrace provide a minimum estimation of terrace formation prior to ~15 ka (Logan, 1987; Johnson et al., 2001). Additional radiocarbon ages obtained from deposits in an upstream tributary similar in morphology to the Buck Creek Terrace place its deposition between ~28-22 ka (Johnson et al., 2001). Recently, Dort and Mandel (2011) reported on two Buck Creek surfaces in upstream tributaries of the Kansas River: an upper Buck Creek, predominately comprised of fine-grain material, and a lower Buck Creek, which contained abundant sand. Beck (1959. p. 35) also documented sand and gravel in the lower stratigraphy of the Buck Creek Terrace east of Wamego, Kansas.

The Newman Terrace, the most widely distributed surface within the river valley, is comprised of fine-grained sediments and contains a well-developed basal soil dating ~14-10 ka and overlain by several less-developed Holocene buried soils. The lowest terrace in the Kansas River valley is the Holliday Terrace Complex (McCrae, 1954), situated ~2 m above the floodplain, is characterized by abandoned meander scrolls and channels (oxbow features). Radiocarbon and unpublished OSL ages obtained from the Holliday Terrace place its deposition between ~4–1 ka (Johnson et al., 2001).

Aeolian dunes mantle the Menoken Terrace on the northern side of the Kansas River valley, except west of Wamego, Kansas, where dunes occur directly on the adjacent bedrock upland (Fig. 5.2). Figure 5.3 demonstrates the position of the aeolian dunes in the Kansas River valley to that of mapped Menoken, Newman, and Holliday Terrace deposits. Dune relief averages ~15 m, though the thickness of aeolian sediment decreases abruptly with distance from the Kansas River. The dune field has a small footprint, and, in many cases, only one or two individual dunes occur in any given area (Rockel et al., 2010). Dunes of the study area are well-stabilized by a mosaic of cropland/grassland/rangeland, shrubs, and deciduous forest vegetation, though original land records prior to settlement document tall-grass prairie (Kuchler, 1967). The dune field appears to have been stable considerably longer than most dune fields within the Great Plains due to the atypical degree of surface soil development observed at several sites (Appendix IV).

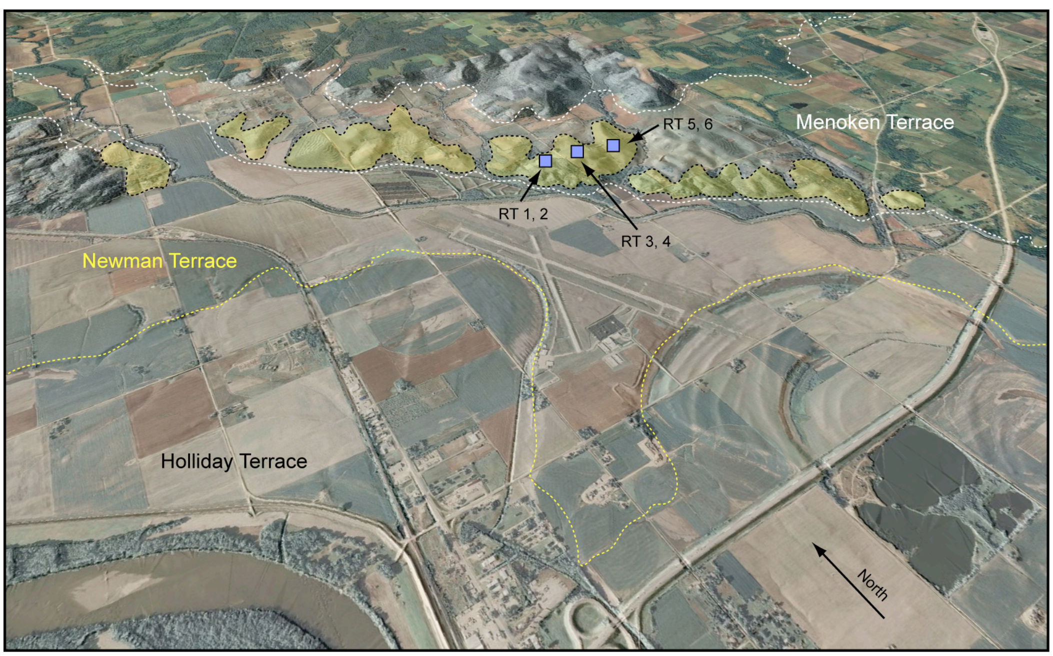

Figure 5.3. Oblique view of the Kansas River valley northeast of Lawrence, Kansas showing the relationship between mapped aeolian dunes (yellow shading) and terrace deposits. Image background is 2008 NAIP imagery draped over LiDAR derived Hillshade DEM.

5.3. Methods and results

Eight dunes were sampled for chronological control: four sites are on the crests of dunes (RT 1, 3, 5; DNA 1), three were interdune areas (RT 2, 4, 6) and one was located within aeolian deposit cut by fluvial incision (DAG 1). OSL samples were collected from profiles within soil pits at each site, except at the RT 3 site where a hand auger was used to collect samples. In essence, OSL dating records the last time a quartz grain was exposed to the sun, i.e., the time since burial following light exposure during aeolian mobilization. Samples were collected directly from dune sediment using opaque tubes, which protect the sample from any light exposure, and analysis was conducted using the single aliquot regenerative (SAR) protocol (Murray and Wintle, 2000), following pretreatment and SAR procedures outlined in Halfen et al. (2012).

Optical samples from the KRD are well behaved and yielded reliable ages (Table 5.1), which were verified through multiple intrinsic laboratory tests. The suite of OSL ages reported in this study can be divided into four groups: sand deposition and subsequent pedogenesis ~48 ka; aeolian deposition ~35–28 ka; dune erosion ~6–4 ka, and aeolian activity ~0.8 ka. Two of these age groups (~48 ka, ~0.8 ka) were collected from the Dagen Site (Fig. 5.2; 5.4). Stratigraphy of this site is characterized by ~1 m of thin (<3 cm) laminations of sand and silt, which also contain lamellae, underlain by sandy-clay sediment interpreted as aeolian sand. Overlying laminated sediment is interpreted to be slope-wash originating from upland erosion of nearby dunes, which may contain a small component of aeolian sediment as well (layers of loess). At 60 cm depth, laminations are disturbed by burrows and structures that appear to be loading structures (Fig. 5.5), which may well be the result of soft-sediment deformation, but could also be the result of source-point deformation due to localized bioturbation (Jennings et al., 2006; Platt and Hasiotis, 2006). The latter may well have occurred at the Dagen site because the majority of deformation is in the downward direction, with minimal disturbance of the underlain sandy-clay sediment, which is atypical of fluvial loading structures (Platt and

Table 5.1. Equivalent dose, dose rate, and age estimates for the Kansas River dunes

Field #	Depth (m)	U[a]	Th[a]	K_2O (wt %)	In Situ H_2O (%)[b]	Dose Rate (Gy/ka)	De (Gy) ± 1 Std. Err.	Aliqt. (n/n)[c]	Optical Age ± 1 σ
RT 1	1.60	1.4	4.9	1.8	3.4	2.46 ± 0.13	76.4 ± 3.7	46/48	31,100 ± 2230
RT 2	1.80	2.9	12	1.6	3.4	3.12 ± 0.17	15.0 ± 0.9	47/48	4810 ± 400
RT 3	1.40	1.5	5.7	2.3	11.0	2.46 ± 0.24	87.4 ± 4.1	20/24	34,400 ± 4100
RT 4	0.80	2.8	9.9	2.0	3.7	3.37 ± 0.18	20.4 ± 2.5	45/48	6040 ± 820
RT 5	1.60	2.5	8.8	2.0	1.6	3.29 ± 0.18	116.1 ± 4.7	47/48	35,300 ± 2400
RT 6	1.45	3.0	12	1.5	2.2	3.08 ± 0.17	18.6 ± 4.7	45/48	6010 ± 370
DAG 1	0.6	1.1	4.5	1.4	6.6	2.14 ± 0.13	1.5 ± 0.1	26/27	820 ± 80
DAG 2	1.1	1.1	4.2	1.9	10.2	2.01 ± 0.19	97.3 ± 2.4	28/33	48,300 ± 5100
DNA 1	1.4	0.7	2.7	2.1	1.8	2.14 ± 0.13	60.5 ± 1.6	27/29	28,200 ± 2300

[a] Uranium and thorium are reported in ppm.
[b] Assumes 100% error.
[c] (accepted/total) aliquots.

Hasiotis, 2006). An OSL sample (DAG 1-1) collected within the lowermost undisturbed laminated sediment at ~50 cm depth yielded an age of 820 ± 80 years ago. An OSL sample (DAG 1-2) collected from the lower sandy-clay sediment dated to 48,300 ± 5100 years ago.

Four ages from the KRD reflect aeolian deposition between ~35–28 ka (RT 1, 3, 5; DNA 1). Sites displayed markedly similar stratigraphy characterized by well developed A-AB-Bt-C soils (Fig. 5.6) and OSL samples (DNA 1, RT 1, RT 3, RT 5) collected from ~1.5 m within the C horizon at each site yielded ages of 28,200 ± 2300, 31,100 ± 2230, 34,400 ± 4100, and 35,300 ± 2400 years ago.

Four additional OSL samples were collected from dune swale sediments (RT 2, 4, 6), which were similar in profile and sedimentary characteristics (e.g., texture and structure) to those of the dune crests, however one significant difference was an apparent over-thickening of A horizon material within the dune swale (Fig. 5.7). This over-thickening is believed to be the result of downslope movement of sediment into the interdune basins, though accumulation of sediment due to aeolian activity can not be

Figure 5.4. Stratigraphy of the Dagen Site. Horizontal laminations of sand (lighter material), silt (reddish brown), and lamellae (burnt orange layers in the top ~20 cm) are found throughout the upper 100 cm of the profile, though, at 60 cm, the layers become disturbed. Aeolian sediment is documented within the profile at 1 m and continues to an unknown depth.

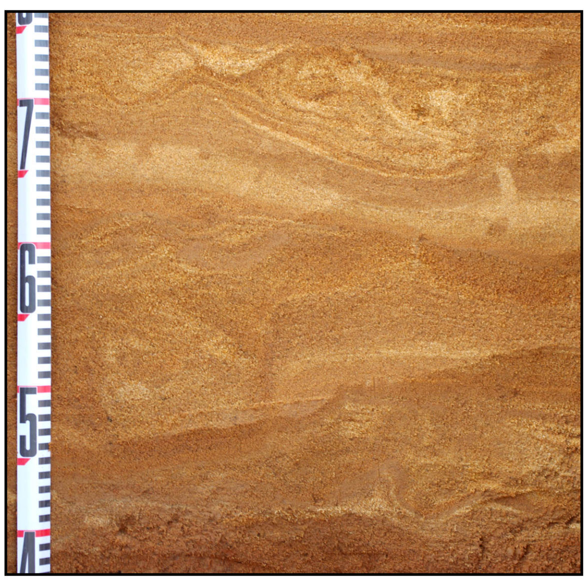

Figure 5.5. Close up of source-point deformation documented at the Dagen site. The lower aeolian sediment is located at the very bottom on the image.

Figure 5.6. Stratigraphy of the RT 3 site, a characteristic representation of the sample site located on dune crests (e.g., RT 1, 3, 5; DNA 1).

excluded as a hypothesis for the over-thickened sediment either. OSL results from samples (RT 2, RT 6, RT 4) collected within dune swale C horizons yielded ages of 4,810 ± 400, 6,010 ± 370, and 6030 ± 820 years ago.

5.4. Discussion

Optical ages from the KRD provide an important chronology of past dune building events, which in turn is important for estimating past landscape stability in the central Great Plains. The earliest evidence of landscape instability is recorded in the lower sandy clay unit at the Dagen site ~48 ka (Figs. 5.2, 5.4). Interpretation of this sandy-clay sediment is limited because only the upper 30 cm was exposed; however, based on multiple lines of evidence, including geomorphic position, texture, and soil

Figure 5.7. Stratigraphy of the RT 2 site, a characteristic representation of the sample sites located within interdune basins (e.g., RT 2, 4, 6). The entire 2 m profile could not be captured in the photograph. An OSL sample was collected within the C horizon at the base of the profile away from any visible signs of bioturbation, which is clearly evident in this profile.

survey maps, the lower sediment at the Dagen site is interpreted as aeolian sand. For example, no Kansas River alluvial deposits have been mapped at this elevation nor are these upslope sediments, which could be a source for a colluvial. Evidence for alluvial deposition prior to ~44 ka was documented in the Abilene dunes only ~40 km upstream of the Dagen Site (Hanson et al., 2010), though that alluvial surface was only ~20 m above the modern Solomon River (primary southern tributary of the Kansas River), whereas the Dagen site is ~40 m above the modern Kansas River.

If aeolian activity occurred ~48 ka, as is suggested at the Dagen site, then it is relatively anomalous when compared to other paleoclimatic records; for example, the age falls between H6 and H5, a period with relatively unpronounced DO events (Fig. 5.8A),

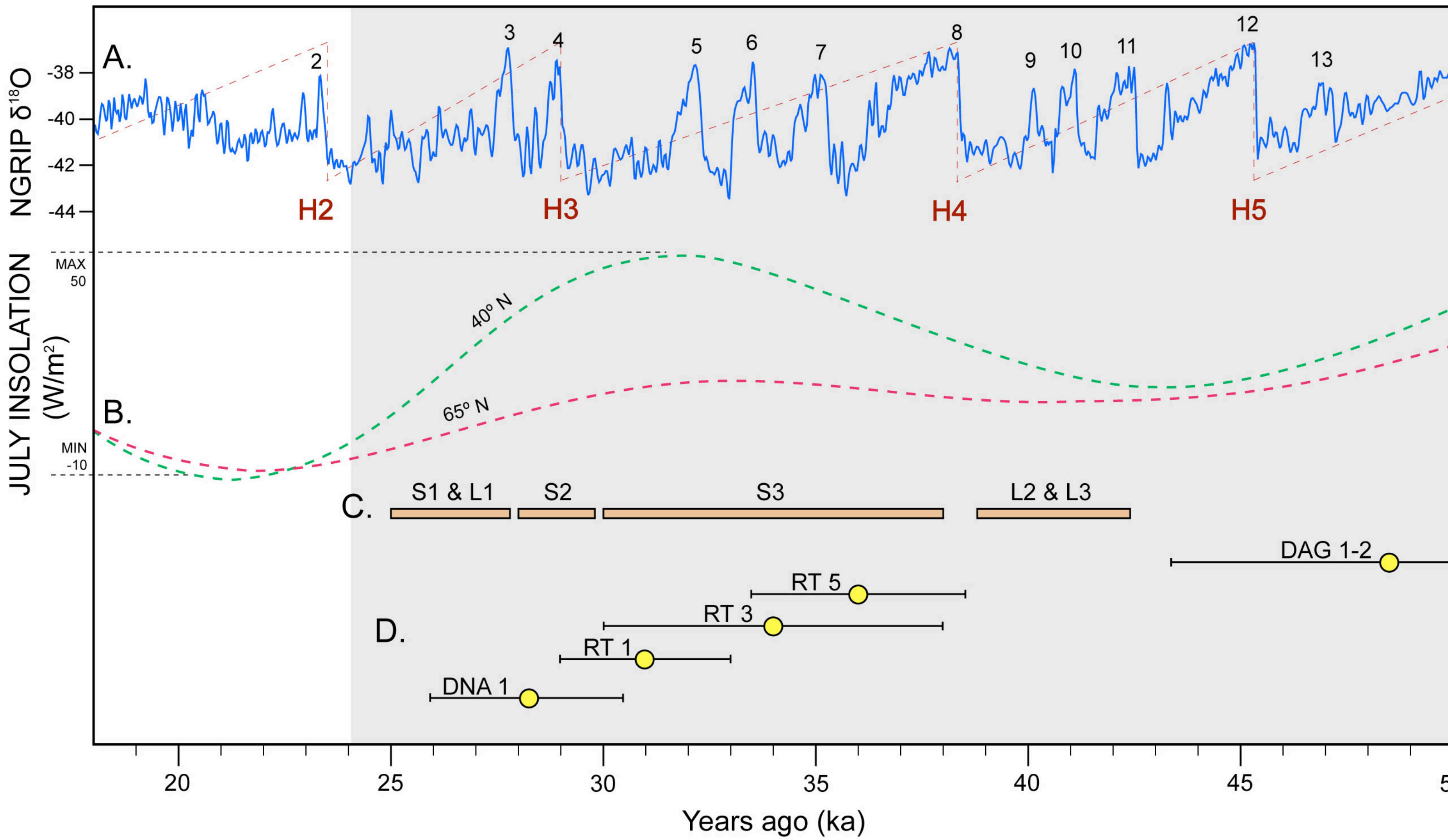

Figure 5.8. Multiple climate proxy records for the period of 18–50 ka. Grey shading=MIS 3, white=MIS 2. A) Greenland NGRIP $\delta^{18}O$ temperature reconstruction (NGRIP Member, 2004). B) departure in summer insolation from the present for 40° N and 65° N (Berger and Loutre, 1991). C) Gilman Canyon Formation loess (L) deposition and soil formation (S) record (Johnson et al., 2007). D) OSL ages and errors for the MIS 3 dune ages reported in this study (see Table 5.1).

near average solar output (Fig. 5.8B), cooler North American mid-continent temperatures as recorded in the regional speleothem record (Dorale et al., 1998; Serefiddin et al., 2004), and little evidence of aeolian activity elsewhere, i.e., most loess records record stability and the formation of the Sangamon Soil (e.g., Johnson et al., 2007; Muhs et al., 2008). Pye et al. (1995) provided thermoluminescence ages of ~64 and ~48 ka from what were believed to be aeolian sands underlying the Gilman Canyon Formation in the Nebraska Sand Hills, though the authors suggest further work was needed to clarify their pre-Gilman Canyon chronostratigraphy in this region (Pye et al., 1995, p. 85).

The next period of aeolian activity in the KRD is documented between ~35 and 28 ka at four sites. These ages were collected within ~2 m of the dune crest below well developed surface soils, indicating that they represent the last period of dune mobilization, and therefore, can be used as minimum estimates for when the KRD stabilized. All four ages date towards the latter part of MIS 3, and three ages date between Heinrich events 4 and 3 (Fig. 5.8A). The latter part of MIS 3 is characterized from the ice-core and marine records as having six DO events (8–3) and modeled to have increased summer insolation (Berger and Loutre, 1991), which Johnson et al. (2007) argued resulted in July temperatures as high as those of today. Presley et al. (2010) documented soil formation within upland loess deposits ~100 km south of the Kansas River between ~32–26 ka, which closely matches the timing of soil formation documented by Johnson et al. (2007) in the Gilman Canyon Formation of Nebraska. Consequently, regional soil formation within Great Plains loess deposits further supports the speculation that ages from the KRD represent the stabilization of the dune field.

While OSL ages from this study indicate stabilization in the KRD, the cause of dune construction during MIS 3 is still unresolved, however given conditions needed to form aeolian dunes on the Great Plains (abundant and available sediment and winds), dune construction probably resulted from either drought or rapid influxes of sediment from the Kansas River. The location of the KRD immediately adjacent to the Kansas

River suggests that dune activity was related to changes in Kansas River fluvial system, though changes to Great Plains fluvial system could also indicate drought (Hall, 1990; Daniels and Knox, 2005).

Four alluvial terraces have been identified within the Kansas River valley, and one of these terraces may have been the sediment source for the KRD. The oldest of these terraces, the Menoken, is likely not the sediment source because: 1) the KRD is located directly above the Menoken Terrace, not adjacent to it; 2) the terrace is dominated by silt and clay textures; and 3) glacial boulders in the terrace fill yield ages too old to have formed the KRD (Aber, 1991; Gosse et al., 1997). The next youngest terrace, the Buck Creek, is limited mostly to the western half of the Kansas River valley (Fig. 5.2). Radiocarbon ages from loess mantling and soil within the Buck Creek Terrace place a minimum age of terrace formation at ~15 ka (Logan, 1987; Johnson et al., 2001), and radiocarbon ages from upstream tributary fill similar to the Buck Creek Terrace dated ~28–22 ka (Johnson, 2001).

Though the Buck Creek Terrace was originally identified as being comprised of silt and clay (Davis and Carlson, 1952), Beck (1959) documented that the lower stratigraphy of the terrace east of Wamego, Kansas was comprised of sands and gravel. Dort and Mandel (2011) also described a sandy lower Buck Creek unit in tributaries of the upper Kansas River, which, based on radiocarbon ages and site stratigraphy, was estimated to be older than the Buck Creek Terrace in the main river valley, however hydraulic and sonic coring of the Buck Creek Terrace at the type locality in the Kansas River valley northwest of Lawrence, Kansas revealed no sandy lower unit (Rockel et al., 2010). Lastly, the Newman Terrace and Holliday Terrace Complex can be excluded as a sediment source for the KRD in that available age data indicate the terrace fill accumulated during the Holocene.

Based on the existing chronostratigraphy of terrace fills within the Kansas River valley, the most probable source of aeolian sediment is a lower sandy unit of the Buck

Creek Terrace, which deflated following abandonment. Given the evidence for a lower sandy Buck Creek unit in upstream tributaries of the Kansas River (Dort and Mandell, 2011), and a lack of that evidence in the main river valley (Rockel et al., 2010), this study proposes that the Buck Creek Terrace was originally composed of two alluvial units: an older sandy unit and a fine-grain unit, which was deposited subsequent to the sandy unit and after ~28 ka. If a sandy unit was deposited within the Kansas River basin prior to ~28 ka, then that unit could have served as the sediment source for the KRD. At present, however, this origin is speculative, and further analysis (e.g., geochemical, mineralogical) of Buck Creek Terrace fill in the Kansas River valley is necessary.

There is clear evidence that aeolian dunes of the KRD are responsive to climate changes as evidenced by middle-Holocene instability recorded in the accumulation of sediment in dune swale sample sites ~6000–4000 years ago. The KRD at this time did not fully activate, instead evidence supports a reduction in stabilizing vegetation, probably associated with the Middle Holocene Climatic Optimum (~9000–5000 years ago: Baker, 2000; Fritz et al., 2001; Grimm et al., 2011), resulting in increased surface erosion from the dune crest which then accumulated within the interdune basins. Accumulation of fine-grained aeolian sediments within the interdune basins at this time can not be excluded as a potential sediment source either, though if this were the case, these deposits should be found throughout the river valley, which they are not. The presence of well-developed surface soils within the KRD likely suppressed dune activity during this time. A similar process was observed in the Cimarron Bend of Oklahoma where Holocene-age dunes with Bt horizons remained stable while those dunes with no pedogenic fine particles activated in response to drought (Werner et al., 2011).

Despite being supported by a single age, the burial of older aeolian sediment by upslope aeolian sediments at the Dagen site ~800 years ago may also indicate a period of decreased vegetation cover associated with well-documented droughts related to climate change during the MCA. Studies have attempted to document the eastward propagation

MCA droughts in the eastern Great Plains from the activation records of dune fields at ~97º–98º W longitude (Hanson et al., 2009; 2010; Halfen et al., 2012), and, although no evidence from the KRD (~96º W longitude) indicates dune reactivation, landscape instability is documented within at least one site ~800 years ago, which provides an indication that droughts extended well into the eastern Great Plains during the MCA.

5.5. Conclusions

Optical ages from the KRD reveal a chronology of landscape change during the late Pleistocene in MIS 3. Four ages, reflective of dune field stability, suggest the KRD stabilized between Heinrich events 4 and 3, which correlates to peaks in summer insolation and to Gilman Canyon Formation soil development. Kansas River dune sediment was likely winnowed from the lower Buck Creek Terrace, which may account for the lack of a sand component in Buck Creek Terrace fill. The KRD remained responsive to climate changes as evidenced by erosion during expanded periods of drought throughout the Holocene. This study highlights the importance of deriving OSL chronologies for smaller, lesser-known dune fields in the Great Plains and illustrates that dune fields, under certain conditions, may contain an extensive record of late-Pleistocene paleoclimate. Further analysis of other Pleistocene dune fields will help to build a Pleistocene dune field activation database, similar to that which currently exists for the Holocene. Finally, this study is significant because it documents the only known Great Plains dune field to have formed during and remained stable since MIS 3.

Chapter 6

SUMMARY

6.1. Research synopsis

This dissertation presents new data on the timing and paleoclimatic significance of prehistoric dune field activity in Kansas. Using a combination of absolute dating techniques (optically stimulated luminescence (OSL) and radiocarbon (^{14}C)), new chronologies of dune field activity were created from three understudied dune fields in Kansas: the Kansas River dunes, Hutchinson dunes, and Arkansas River dunes. These new chronologies indicate, in part, that prehistoric dune activity recorded in Kansas dune fields was the result of drought, which desiccated stabilizing vegetation allowing for subsequent aeolian sedimentation. This research has also highlighted the complexities of correlating dune field activity across the Great Plains in that dune fields of Kansas were not only active in response to drought, but at times were active in response to rapid influxes of sediment. Evidence differentiating drought-induced and non-drought-induced dune activity was presented within this dissertation, however continued research on Great Plains dune fields will help affirm these conclusions.

A principle component of this dissertation is the new chronological data presented within, which collectively records 50,000 years of dune field activity in Kansas. This research has added 127 new optically stimulated luminescence ages to the current Great Plains data set, which account for nearly 25% of the total luminescence ages reported for the entire U.S. Great Plains. Like elsewhere in the Great Plains, dune fields in Kansas are responsive to well-documented droughts associated with major climatic shifts, such as the Middle Holocene Climatic Optimum, Medieval Climatic Anomaly (MCA), and Little Ice Age (LIA). A unique activation chronology, which also records dune field response to climate, was established for the Kansas River dunes. Dune activity was documented during Marine Isotope State (MIS) 3, making the Kansas River dunes the only known Great Plains dune field to have formed during and remained stable since MIS 3.

6.2. Summary of conclusions

6.2.1. Chapter 2

This chapter presents a critical review of the current status and future prospectus of Great Plains dune field chronologies. Additionally, this chapter provides a repository for all chronological data from Great Plains dune fields, which can be accessed for future studies. The principle conclusions of this chapter are:

- Though chronologies of dune field activity (and stability) can be used to determine regional paleoclimate signals, caution is warranted because of interplay of localized factors, which may cause a dune field to activate and overprint a signal of regional climate.
- Correlating the timing of drought across the Great Plains is improved by the advancements of dating techniques used to produce chronologies, but may be hindered due to unintentional dune field sampling bias.
- Future research on Great Plains dune fields, including better maps and new OSL-based chronologies of dune activity, will help better address problems with regional drought correlation.

6.2.2. Chapter 3

A new OSL chronology, which spans the last 2200 years, is presented for the Hutchinson dunes in central Kansas, the third and southernmost of three dune fields that collectively span a 400 km north–south transect of the eastern Great Plains. Primary conclusions of this study include:

- Three major episodes of dune activity occurred ~2100–1800, ~1000–900, and after ~600 years ago, especially within the past 420–70 years.

- Activity ~1000–900 years ago correlates to the height of warming during the MCA.
- Widespread dune activity during the past 600 years, which peaked at ~320 and ~200 years ago, correlates with the coolest periods of the LIA.
- Dune activity in the Hutchinson dunes during the MCA correlates well with available proxy data and dune records from the region, including other eastern-margin dune fields, and suggests that one or more severe droughts were occurring throughout most of the Great Plains at this time.
- Activity during the LIA, unlike that of the MCA, does not correlate with other eastern margin dune fields, but does with those in western Kansas, Colorado, Oklahoma, and Texas and with other regional proxies, suggesting that LIA droughts, unlike those associated with the MCA, were less intense and/or geographically limited.
- LIA droughts were still significant as evidenced by the migration of large dune forms in the Hutchinson dunes at this time.

6.2.3. Chapter 4

This chapter provides a new OSL- and ^{14}C-based chronology of dune activity for the Arkansas River dunes (ARD) in west-central Kansas, which was used to document the formation and subsequent reactivation of the dune field. Significant conclusions of this chapter include:

- Multiple alluvial fills underlie the ARD and were deposited ~43,000–42,000 years ago, ~30,000–24,000 years ago, and between ~22,000–13,000 years ago.
- About 16,000 years ago, morphology of the Arkansas River changed from a single meandering channel system to a broad braided channel system in response to collapse of the Pinedale glaciers in the upper Arkansas River basin.

- Aeolian activity in the ARD began ~16,000 years ago with the formation of the sand sheet and dune field south of the Arkansas River. Large south-trending transverse dunes formed at this time in at least one part of the dune field.
- Episodic aeolian activity occurred in the ARD between ~16,000 years ago and ~4300 years ago.
- Significant episodes of aeolian activity occurred in the ARD after ~1500 and ~900 years ago, and within the past 600 years, which reflect drought-induced dune activity.

6.2.3. Chapter 5

Chapter 5 presented a new OSL chronology for the previously unstudied Kansas River dunes (KRD) in north-eastern Kansas. The primary conclusions of this chapter are:

- OSL ages document dune activity in the KRD from multiple sites ~35–28 ka.
- Major dune building in the KRD appears to have occurred within latter part of MIS 3 between Heinrich events 4 and 3.
- Ages representing final dune stability in the KRD are correlative to other, but limited paleoclimatic records of the Great Plains suggest warmer atmospheric conditions helped stabilize the dune field.
- Chronological and morphological data suggest that initial dune field formation is linked to the lower Buck Creek terrace formation, though, this hypothesis requires further vetting.
- The KRD are the only known Great Plains dune field to have formed during and remained stable since MIS 3.

6.3. Research contribution

This research has made significant contributions to the fields of aeolian research and Quaternary science. The primary contributions of this research include a new extensive data set of OSL ages which reflect prehistoric Great Plains dune field activity, new information on the spatial and temporal patterns of late-Holocene megadroughts, and evidence of Great Plains dune construction during MIS 3, the only known record in the Great Plains.

Arguably the most significant contribution of this dissertation is the chronological data set, which has added over 127 new OSL and ^{14}C to the current Great Plains chronological data set. Considering luminescence ages alone, the new OSL ages reported within this dissertation account for nearly 25% of the total U.S. Great Plains luminescence ages. This extensive new data set is currently being incorporated into the Quaternary Dune Atlas, a global database of aeolian activation chronologies, which when complete will "enable regional and global correlation of periods of dune development via construction of time-slice maps of dune activity and stability and their spatial extent" (Lancaster, 2011).

Prehistoric megadroughts were droughts of higher intensity, duration, and geographical distribution than the 1930's Dust Bowl drought and have been identified in the paleoclimatic record, though the timing and spatial coverage is limited, particularly in the Great Plains because the region lacks traditional drought proxies. This research has used dune field activity in Kansas as a proxy for prehistoric drought, and, as a result, spatial and temporal patterns of megadroughts during the MCA and LIA have been refined. In particular, evidence from dune fields in Kansas illustrates drought-induced dune activity following the MCA, though dune activity ceases earlier than most other areas in the Great Plains. Coupled to this are the spatial patterns of MCA megadroughts, which, based on this dissertation research, encompassed most of Kansas. Similar dune field responses to megadroughts during the LIA are also documented in this research;

however, unlike droughts of the MCA, those of the LIA were constrained to the southern and western Great Plains, likely due to a greater influence of La Nina-like conditions.

Lastly, this research has provided specific contributions to the current understanding of MIS 3 landscape history, a window of time that, within the region and globally, is not well understood. This study highlights the potential for smaller Great Plains dune fields to provide significant records of prehistoric dune activity and further asserts that small dune fields should not be overlooked when attempting to develop dune activation chronologies. Future analysis of other Pleistocene dune fields will help to build a Pleistocene activation database, similar to that which currently exists for the Holocene, which in turn will provide important paleoclimatic information for the region.

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Appendix I

RADIOCARBON AND LUMINESCENCE AGES FROM GREAT PLAINS DUNE FIELDS

AI.1. Canadian Great Plains

Province	Dune Field	Study	Yr.	M[a]	Age Dat[b]	Age[c]	± Er.[c]	Cal. Age[d]	Cal. ± Er.[e]
Alberta	Battle River Sand Hills	Wolfe et al. 2004	2004	L	2004	11300	500	11308	500
Alberta	Battle River Sand Hills	Wolfe et al. 2004	2004	L	2004	12800	600	12808	600
Alberta	Bear River Sand Hills	Wolfe et al. 2004	2004	L	2004	13500	1000	13508	1000
Alberta	Bear River Sand Hills	Wolfe et al. 2004	2004	L	2004	13700	1000	13708	1000
Alberta	Beaverhill Creek Sand Hills	Wolfe et al. 2004	2004	L	2004	12500	700	12508	700
Alberta	Chisholm Sand Hills	Wolfe et al. 2004	2004	L	2004	15300	800	15308	800
Alberta	Decrene Sand Hills	Wolfe et al. 2004	2004	L	2004	14800	900	14808	900
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	229	20	247	20
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	260	26	278	26
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	403	27	421	27
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	980	60	998	60
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	2940	200	2958	200
Alberta	Duchess Sand Hills	Wolfe et al. 2002b	2002	L	1994	4540	420	4558	420
Alberta	Economy Creek Sand Hills	Wolfe et al. 2004	2004	L	2004	11800	800	11808	800

Alberta	Edson Sand Hills	Wolfe et al. 2004	2004	L	2004	14000	800	14008	800
Alberta	Fort Assiniboine Sand Hills	Wolfe et al. 2004	2004	L	2004	14500	1000	14508	1000
Alberta	Grovedale Sand Hills	Wolfe et al. 2004	2004	L	2004	14900	1000	14908	1000
Alberta	High Level dunes	Wolfe et al. 2007b	2007	L	2001	10300	900	10311	900
Alberta	High Level dunes	Wolfe et al. 2007b	2007	L	2001	11000	1000	11011	1000
Alberta	High Level dunes	Wolfe et al. 2007b	2007	L	2001	11700	1000	11711	1000
Alberta	High Level dunes	Wolfe et al. 2007b	2007	L	2001	13400	1200	13411	1200
Alberta	Holmes Crossing Sand Hills	Wolfe et al. 2004	2004	L	2004	14900	1000	14908	1000
Alberta	Hondo Sand Hills	Wolfe et al. 2004	2004	L	2004	14200	700	14208	700
Alberta	Lac La Biche Sand Hills	Wolfe et al. 2004	2004	L	2004	12600	600	12608	600
Alberta	Lodgepole Sand Hills	Wolfe et al. 2004	2004	L	2004	14100	1800	14108	1800
Alberta	Nelson Lake Sand Hills	Wolfe et al. 2004	2004	L	2004	14500	900	14508	900
Alberta	Pipestone Sand Hills	Wolfe et al. 2004	2004	L	2004	14200	900	14208	900
Alberta	Redwater Sand Hills	Wolfe et al. 2004	2004	L	2004	11700	600	11708	600
Alberta	Rocky Mt. House Sand Hills	Wolfe et al. 2004	2004	L	2004	11600	800	11608	800
Alberta	Rocky Mt. House Sand Hills	Wolfe et al. 2004	2004	L	2004	12400	800	12408	800
Alberta	Stony Plain Sand Hills	Wolfe et al. 2004	2004	L	2004	6200	600	6208	600
Alberta	Stony Plain Sand Hills	Wolfe et al. 2004	2004	L	2004	12000	600	12008	600

Alberta	Stony Plain Sand Hills	Wolfe et al. 2004	2004	L	2004	13400	800	13408	800
Alberta	Watino Sand Hills	Wolfe et al. 2004	2004	L	2004	12900	800	12908	800
Alberta	Windfall Sand Hills	Wolfe et al. 2004	2004	L	2004	15700	1600	15708	1600
Manitoba	Brandon Sand Hills	David 1971	1971	R	1950	340	130	460	157
Manitoba	Brandon Sand Hills	David 1971	1971	R	1950	820	140	822	223
Manitoba	Brandon Sand Hills	David 1971	1971	R	1950	1480	150	1451	321
Manitoba	Brandon Sand Hills	David 1971	1971	R	1950	2120	150	2153	376
Manitoba	Brandon Sand Hills	David 1971	1971	R	1950	3710	180	4115	479
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	140	160	210	152
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	430	260	530	200
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	490	160	603	115
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	670	180	692	114
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	890	260	913	214
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	920	600	923	548
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	920	280	958	248
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1090	360	1057	314
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1200	280	1190	231
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1260	260	1227	238
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1290	260	1235	243

Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1310	1320	1464	1147
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1370	400	1372	404
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1430	240	1379	252
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1510	300	1491	309
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1510	400	1521	408
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1600	180	1574	186
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	1910	260	1908	308
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2150	240	2156	270
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2150	300	2196	359
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2180	220	2186	242
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2205	220	2257	275
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2320	320	2431	381
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2420	280	2522	320
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2530	280	2681	310
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2690	680	2852	804
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2780	680	2948	833
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	2950	640	3181	780
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	3680	360	4071	447
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	4180	300	4740	390
Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	4540	1000	5140	1223

Manitoba	Brandon Sand Hills	Wolfe et al. 2000	2000	R	1950	4560	1480	5175	1781
Manitoba	Brandon Sand Hills	Wolfe et al. 2002a	2002	L	2000	2050	120	2062	120
Manitoba	Brandon Sand Hills	Wolfe et al. 2002a	2002	L	2000	3040	150	3052	150
Manitoba	Brandon Sand Hills	Wolfe et al. 2002a	2002	L	2000	3440	150	3452	150
Manitoba	Brandon Sand Hills	Wolfe et al. 2002a	2002	L	2000	4040	150	4052	150
Manitoba	Brandon Sand Hills	Wolfe et al. 2002a	2002	L	2000	5600	270	5612	270
Saskatchewan	Bigstick Sand Hills	Wolfe et al. 2001	2001	L	1995	85	5	102	5
Saskatchewan	Bigstick Sand Hills	Wolfe et al. 2001	2001	L	1995	91	5	108	5
Saskatchewan	Bigstick Sand Hills	Wolfe et al. 2001	2001	L	1995	117	6	134	6
Saskatchewan	Bigstick Sand Hills	Wolfe et al. 2001	2001	L	1995	151	5	168	5
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	92	7	109	7
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	163	7	180	7
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	168	9	185	9
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	252	17	269	17
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	307	21	324	21
Saskatchewan	Burstall Sand Hills	Wolfe et al. 2001	2001	L	1995	4760	330	4777	330
Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	3150	80	2344	183
Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	7070	115	7930	193
Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	7640	150	8538	315
Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	8100	120	9040	342

Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	8160	125	9146	366
Saskatchewan	Dundurn Sand Hills	Turchenek et al. 1974	1974	R	1950	9940	160	11630	495
Saskatchewan	Dundurn Sand Hills	Lian et al. 2002	2002	L	2001	2760	320	2771	320
Saskatchewan	Dundurn Sand Hills	Lian et al. 2002	2002	L	2001	5210	220	5221	220
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	145	20	156	20
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	215	17	226	17
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	1480	60	1491	60
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	1980	80	1991	80
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	2740	120	2751	120
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	3040	140	3051	140
Saskatchewan	Elbow Sand Hills	Lian et al. 2002	2002	L	2001	5690	240	5701	240
Saskatchewan	Elbow Sand Hills	Wolfe et al. 2007a	2006	L	2007	320	20	325	20
Saskatchewan	Elbow Sand Hills	Wolfe et al. 2007a	2007	L	2007	140	20	145	20
Saskatchewan	Elbow Sand Hills	Wolfe et al. 2007a	2007	L	2007	235	15	240	15
Saskatchewan	Fort a la Corne Sand Hills	Wolfe et al. 2006	2006	L	2000	6620	310	6632	310
Saskatchewan	Fort a la Corne Sand Hills	Wolfe et al. 2006	2006	L	2000	6810	300	6822	300
Saskatchewan	Fort a la Corne Sand Hills	Wolfe et al. 2006	2006	L	2000	9750	690	9762	690
Saskatchewan	Gowen Site	Wolfe et al. 2002a	2002	R	1950	9460	240	10841	625
Saskatchewan	Grandora	Wolfe et al. 2002a	2002	R	1950	3730	80	4144	218

Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	115	5	132	5
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	116	5	133	5
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	129	6	146	6
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	143	9	160	9
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	216	11	233	11
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	640	60	657	60
Saskatchewan	Great Sand Hills	Wolfe et al. 2001	2001	L	1995	930	50	947	50
Saskatchewan	Manito Lake Sand Hills	Wolfe et al. 2006	2006	L	2000	2550	210	2562	210
Saskatchewan	Manito Lake Sand Hills	Wolfe et al. 2006	2006	L	2000	4960	190	4972	190
Saskatchewan	Manito Lake Sand Hills	Wolfe et al. 2006	2006	L	2000	6070	310	6082	310
Saskatchewan	Manito Lake Sand Hills	Wolfe et al. 2006	2006	L	2000	6940	310	6952	310
Saskatchewan	Moon Lake	Wolfe et al. 2002a	2002	R	1950	4100	90	4691	211
Saskatchewan	Nisbet Sand Hills	Wolfe et al. 2006	2006	L	2000	5230	250	5242	250
Saskatchewan	Nisbet Sand Hills	Wolfe et al. 2006	2006	L	2000	11800	500	11812	500
Saskatchewan	North Battleford Sand Hills	Wolfe et al. 2006	2006	L	2000	5580	270	5592	270
Saskatchewan	North Battleford Sand Hills	Wolfe et al. 2006	2006	L	2000	6510	280	6522	280
Saskatchewan	Pike Lake	Wolfe et al. 2002a	2002	R	1950	820	60	798	69
Saskatchewan	Pike Lake	Wolfe et al. 2002a	2002	R	1950	2400	70	2540	146
Saskatchewan	Pike Lake	Wolfe et al. 2002a	2002	R	1950	2450	70	2597	182
Saskatchewan	Pike Lake	Wolfe et al. 2002a	2002	R	1950	3470	70	3802	176

Saskatchewan	Pike Lake	Wolfe et al. 2002a	2002	R	1950	3510	70	3859	180
Saskatchewan	Qu' Appelle Valley	Wolfe et al. 2002a	2002	R	1950	1460	140	1411	281
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	94	6	111	6
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	94	6	111	6
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	109	8	126	8
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	116	7	133	7
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	117	7	134	7
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	123	6	140	6
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	125	5	142	5
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	137	9	154	9
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	152	8	169	8
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	160	10	177	10
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	168	7	185	7
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	174	8	191	8
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	180	8	197	8
Saskatchewan	Seward Sand Hills	Wolfe et al. 2001	2001	L	1995	185	8	202	8
Saskatchewan	Tunstall Sand Hills	Wolfe et al. 2001	2001	L	1995	68	12	85	12
Saskatchewan	Westerham Sand Hills	Wolfe et al. 2001	2001	L	1995	105	8	122	8
Saskatchewan	Westerham Sand Hills	Wolfe et al. 2001	2001	L	1995	129	9	146	9

a Dating method: L = Luminescence; R = Radiocarbon. See Chapter 2 for specific dating technique.

b Age Datum: 1950 is assumed for all ^{14}C ages; date of publication is assumed as the age datum for all luminescence samples unless otherwise reported by the original authors.

c Age and Error: As originally reported (see Chapter 2 for details).

d Calibrated Age: Calibrated to "years before" AD 2012.

e Calibrated Error: All ^{14}C ages are shown with 2σ errors; all luminescence ages are shown with their original σ error (see Chapter 2 for details).

AI.2. Northern U.S. Great Plains

Province	Dune Field	Study	Yr.	M[a]	Age Dat[b]	Age[c]	± Er.[c]	Cal. Age[d]	Cal. ± Er.[e]
Minnesota	Winnibigoshish dunes	Grigal et al. 1976	1976	R	1950	5040	105	5852	201
Minnesota	Winnibigoshish dunes	Grigal et al. 1976	1976	R	1950	7910	155	8831	366
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	170	60	241	123
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	290	60	447	115
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	330	60	459	108
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	540	60	640	75
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	570	60	648	72
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	570	50	609	28
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	1030	60	990	133
North Dakota	Minot dunes	Muhs et al. 1997	1997	R	1950	1260	60	1239	117
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	4925	65	5735	92
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	6480	310	7367	631
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	7180	90	8069	178
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	7240	150	8143	294
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	7370	150	8250	259
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	7550	80	8395	148
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	7675	175	8643	413
North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	9045	90	10231	263

North Dakota	Sheyenne Delta dunes	Running 1995	1995	R	1950	9130	150	10356	408
North Dakota	Sheyenne Delta dunes	Running 1996	1996	R	1950	580	60	651	71
North Dakota	Sheyenne Delta dunes	Running 1996	1996	R	1950	890	50	886	100
North Dakota	Sheyenne Delta dunes	Running 1996	1996	R	1950	2370	60	2493	122
North Dakota	Sheyenne Delta dunes	Running 1996	1996	R	1950	7590	90	8436	178
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	L	2003	2650	78	2659	78
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	405	140	522	205
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1280	30	1292	59
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1287	41	1294	65
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1310	70	1264	135
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1333	38	1326	44
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1390	70	1356	123
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	1418	38	1395	48
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2070	70	2090	152
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2390	70	2579	199
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2540	39	2628	78

South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2547	40	2629	78
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2790	65	2977	152
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	2950	45	3173	146
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	3640	55	4025	132
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	3654	42	4038	115
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	3800	70	4080	32
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	5850	195	6788	436
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	6340	70	7353	135
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	6870	155	7781	260
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	6910	185	7804	310
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	7790	170	8725	368
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	7859	52	8729	126
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	7910	60	8769	111
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	7990	55	8912	159
South Dakota	White River Badlands sand dunes	Rawling et al. 2003	2003	R	1950	10400	70	12354	244

Wyoming	Casper dunes	Albanese 1974	1974	R	1950	9830	350	11454	1020
Wyoming	Casper dunes	Albanese 1974	1974	R	1950	10060	170	11767	515
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	410	190	412	190
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	410	50	412	50
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	420	40	422	40
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	1000	220	1002	220
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	1760	190	1762	190
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	4070	300	4072	300
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	4260	280	4262	280
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	5140	210	5142	210
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	6100	230	6102	230
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	6670	450	6672	450
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	7020	220	7022	220
Wyoming	Casper dunes	Halfen et al. 2010	2010	L	2010	8150	390	8152	390
Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	1970	77	1986	192

Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	2240	120	1999	40
Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	3460	40	3798	103
Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	3730	50	4162	138
Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	5410	60	6106	41
Wyoming	Casper dunes	Halfen et al. 2010	2010	R	1950	5700	90	6550	186
Wyoming	Ferris dunes	Gaylord 1982	1982	R	1950	2155	125	2159	272
Wyoming	Ferris dunes	Gaylord 1982	1982	R	1950	6460	180	7372	356
Wyoming	Ferris dunes	Gaylord 1982	1982	R	1950	7660	210	8582	480
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	4540	180	5275	401
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	5940	150	6863	363
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	7050	210	8002	378
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	7150	210	8054	379
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	7160	210	8058	379
Wyoming	Ferris dunes	Gaylord 1990	1990	R	1950	7460	190	8343	359
Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	4040	770	4059	770
Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	4160	670	4179	670

Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	4340	620	4359	620
Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	8090	810	8109	810
Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	8260	990	8279	990
Wyoming	Ferris dunes	Stokes and Gaylord 1993	1993	L	1993	8800	880	8819	880

a Dating method: L = Luminescence; R = Radiocarbon. See Chapter 2 for specific dating technique.

b Age Datum: 1950 is assumed for all ^{14}C ages; date of publication is assumed as the age datum for all luminescence samples unless otherwise reported by the original authors.

c Age and Error: As originally reported (see Chapter 2 for details).

d Calibrated Age: Calibrated to "years before" AD 2012.

e Calibrated Error: All ^{14}C ages are shown with 2σ errors; all luminescence ages are shown with their original σ error (see Chapter 2 for details).

AI.3. Central U.S. Great Plains

Province	Dune Field	Study	Yr.	M[a]	Age Dat[b]	Age[c]	± Er.[c]	Cal. Age[d]	Cal. ± Er.[e]
Colorado	Fort Morgan dunes	Forman et al. 1992	1992	R	1950	920	260	971	449
Colorado	Fort Morgan dunes	Forman et al. 1992	1992	R	1950	4765	305	5567	702
Colorado	Fort Morgan dunes	Forman et al. 1992	1992	R	1950	5515	410	6425	901
Colorado	Fort Morgan dunes	Forman et al. 1992	1992	R	1950	9460	490	10937	1345
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	810	90	848	140
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	860	90	861	137
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	910	50	892	97
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	940	110	929	194
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	1000	100	970	186
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	1150	70	1121	126
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	1370	80	1307	167
Colorado	Fort Morgan dunes	Madole 1994	1994	R	1950	1380	90	1308	173
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	5300	500	5317	500
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	5600	700	5617	700
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	6100	500	6117	500

Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	6400	800	6417	800
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	6600	600	6617	600
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	6600	500	6617	500
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	6700	700	6717	700
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	L	1995	13500	1200	13517	1200
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	R	1950	5010	100	5825	178
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	R	1950	7950	90	8864	221
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	R	1950	8030	150	8991	387
Colorado	Fort Morgan dunes	Forman et al. 1995	1995	R	1950	13745	175	16878	433
Colorado	Fort Morgan dunes	Madole 1995	1995	L	1995	3230	250	3247	250
Colorado	Fort Morgan dunes	Madole 1995	1995	L	1995	6940	1300	6957	1300
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	810	90	848	140
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	860	90	861	137
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	910	50	892	97
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	940	110	929	194
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	1000	100	970	186

Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	1150	70	1121	126
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	1370	80	1307	167
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	1380	90	1308	173
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	2860	60	3067	161
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	5640	90	6524	176
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	7870	240	8860	517
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	9010	100	10154	319
Colorado	Fort Morgan dunes	Madole 1995	1995	R	1950	9690	110	11050	286
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	370	50	379	50
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	535	115	544	115
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	595	100	604	100
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	805	105	814	105
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	1060	95	1069	95
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	1065	125	1074	125
Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	2370	210	2379	210

Colorado	Fort Morgan dunes	Clarke and Rendell 2003	2003	L	2003	4850	325	4859	325
Colorado	Greeley dunes	Forman et al. 1992	1992	R	1950	11530	140	13482	287
Colorado	Hudson dunes	Forman and Maat 1990	1990	L	1990	8600	1300	8622	1300
Colorado	Hudson dunes	Forman and Maat 1990	1990	L	1990	8800	1700	8822	1700
Colorado	Hudson dunes	Forman and Maat 1990	1990	R	1950	7270	110	8196	206
Colorado	Hudson dunes	Forman and Maat 1990	1990	R	1950	8280	150	9317	288
Colorado	North Park dunes	Ahlbrandt et al. 1983	1983	R	1950	1070	200	1066	343
Colorado	North Park dunes	Ahlbrandt et al. 1983	1983	R	1950	1250	200	1211	388
Colorado	North Park dunes	Ahlbrandt et al. 1983	1983	R	1950	2110	200	2177	429
Colorado	North Park dunes	Ahlbrandt et al. 1983	1983	R	1950	2830	200	3016	494
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	430	110	435	110
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	430	110	435	110
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	840	210	845	210
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	2710	200	2715	200
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	3960	490	3965	490

Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	5490	410	5495	410
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	6790	500	6795	500
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	7060	550	7065	550
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	9570	810	9575	810
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	14620	1250	14625	1250
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	16130	1350	16135	1350
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	16820	1380	16825	1380
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	17030	1400	17035	1400
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	17700	2100	17705	2100
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	17950	1610	17955	1610
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	18140	1490	18145	1490
Illinois	Green River Lowlands	Miao et al. 2010	2010	L	2007	18420	1420	18425	1420
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	460	80	500	126
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	590	40	657	60
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	840	60	816	80
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	1760	80	1760	181
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	2680	100	2920	207
Illinois	Green River Lowlands	Miao et al. 2010	2010	R	1950	2880	100	3087	241
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	460	40	462	40

Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	610	40	612	40
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	640	70	642	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	710	80	712	80
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	710	60	712	60
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	720	60	722	60
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	750	80	752	80
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	760	70	762	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	760	60	762	60
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	780	70	782	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	780	70	782	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	790	100	792	100
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	820	70	822	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	860	70	862	70
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	1060	120	1062	120
Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	12000	1900	12002	1900

Kansas	Abilene dunes	Hanson et al. 2010	2010	L	2010	13100	1200	13102	1200
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	65	5	77	5
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	70	7	82	7
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	80	10	92	10
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	180	15	192	15
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	190	20	202	20
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	220	20	232	20
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	320	25	332	25
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	340	30	352	30
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	370	30	382	30
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	380	30	392	30
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	420	40	432	40
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	430	30	442	30
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	1490	130	1502	130

Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	6280	670	6292	670
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	8350	680	8362	680
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	8500	680	8512	680
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	8615	840	8627	840
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	9200	820	9212	820
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	9840	880	9852	880
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	12220	950	12232	950
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	12460	990	12472	990
Kansas	Arkansas River dunes	Forman et al. 2008	2008	L	2000	16310	1200	16322	1200
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	1450	80	1455	137
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	3620	90	3986	234
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	5570	70	6446	113
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	5770	60	6619	121

Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	6360	20	7352	38
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	7330	70	8226	157
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	8920	90	10046	250
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	9530	70	10953	240
Kansas	Cimarron Bend dunes	Olson and Porter 2002	2002	R	1950	10130	150	11796	487
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	520	50	527	50
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	630	50	637	50
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	770	70	777	70
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	2530	300	2537	300
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	3570	400	3577	400
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	3590	360	3597	360
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	3620	300	3627	300
Kansas	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	6440	760	6447	760

Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	270	80	440	125
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	380	80	475	127
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	480	100	598	119
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	490	80	603	115
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	550	80	632	104
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	700	80	717	118
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	710	80	724	122
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	810	120	840	160
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	880	80	866	126
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	1030	80	991	166
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	1090	120	1089	248
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	1500	80	1480	133
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	1500	100	1500	180
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	2310	100	2427	255
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	2400	130	2513	302
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	2730	180	2875	452
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	2940	160	3165	346
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	3220	80	3539	160
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	3280	100	3588	202
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	3820	100	4265	243

Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	5370	120	6197	221
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	6160	160	7086	313
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	7850	140	8768	313
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	9050	560	10350	1539
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	10460	720	12051	1788
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	11100	180	13032	329
Kansas	Great Bend Sand Prairie	Arbogast 1996	1996	R	1950	16670	360	19801	816
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	80	10	82	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	80	10	82	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	80	10	82	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	81	10	83	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	90	11	92	11
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	100	10	102	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	100	10	102	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	100	10	102	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	110	10	112	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	110	10	112	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	120	10	122	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	140	30	142	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	140	10	142	10

Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	140	20	142	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	160	20	162	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	160	20	162	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	170	20	172	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	180	10	182	10
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	180	20	182	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	190	20	192	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	190	20	192	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	190	20	192	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	200	20	202	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	210	20	212	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	220	20	222	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	220	20	222	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	220	30	222	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	240	20	242	20

Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	240	30	242	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	240	20	242	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	260	30	262	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	270	30	272	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	270	50	272	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	290	50	292	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	290	20	292	20
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	300	30	302	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	320	50	322	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	320	30	322	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	320	30	322	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	330	40	332	40
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	350	30	352	30
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	420	50	422	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	450	50	452	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	520	50	522	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	604	50	606	50
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	810	70	812	70
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	920	80	922	80
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	920	90	922	90

Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	960	80	962	80
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	960	80	962	80
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	1150	140	1152	140
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	1880	190	1882	190
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	2050	190	2052	190
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	2070	200	2072	200
Kansas	Hutchinson dunes	Halfen et al. 2012	2012	L	2010	2080	200	2082	200
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	490	50	493	50
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	560	50	563	50
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	590	50	593	50
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	670	60	673	60
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	670	60	673	60
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	690	60	693	60
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	690	70	693	70
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	700	60	703	60
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	720	70	723	70

Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	830	90	833	90
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	3440	310	3443	310
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	3634	280	3637	280
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	3720	340	3723	340
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	3990	350	3993	350
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	4170	410	4173	410
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	4360	360	4363	360
Nebraska	Duncan dunes	Hanson et al. 2009	2009	L	2009	5070	430	5073	430
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	860	55	823	75
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	3000	400	3290	933
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	3110	80	3341	202
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	3560	70	3905	158
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	3600	400	4007	1025
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	3810	80	4263	219

Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	4900	500	5602	1202
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	5040	80	5843	141
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	5150	400	5874	940
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	7220	120	8137	249
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	8410	110	9384	231
Nebraska	Nebraska Sand Hills	Ahlbrandt et al. 1983	1983	R	1950	9930	140	11604	451
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	580	80	651	88
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	770	60	781	78
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	1260	130	1227	238
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	1320	70	1270	137
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	1425	55	1401	78
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	1480	80	1470	134
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	3050	60	3292	154
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	3220	80	3539	160
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	3300	70	3599	152
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	3570	80	3947	202
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	3640	90	3994	230

Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	4330	60	4998	119
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	9880	60	11364	108
Nebraska	Nebraska Sand Hills	Loope et al. 1995	1995	R	1950	10670	60	12687	97
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	210	80	225	80
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	250	80	265	80
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	430	100	445	100
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	470	130	485	130
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	750	120	765	120
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	2130	410	2145	410
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	3810	640	3825	640
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	L	1997	5730	710	5745	710
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	R	1950	270	70	242	43
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	R	1950	845	55	817	77
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	R	1950	1590	70	1543	144
Nebraska	Nebraska Sand Hills	Stokes & Swinehar t 1997	1997	R	1950	1620	55	1568	121

Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	1880	190	1858	390
Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	1880	110	1868	257
Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	2290	70	2366	185
Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	5300	100	6159	199
Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	8930	110	10020	298
Nebraska	Nebraska Sand Hills	Stokes & Swinehart 1997	1997	R	1950	9610	80	11020	235
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2003	150	10	159	10
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	340	20	348	20
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	830	50	838	50
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	830	50	838	50
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	830	50	838	50
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	840	60	848	60
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	860	50	868	50
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	880	50	888	50
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1040	70	1048	70
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1060	60	1068	60
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1180	80	1188	80

Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1300	80	1308	80
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1540	110	1548	110
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1540	100	1548	100
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1580	110	1588	110
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1630	120	1638	120
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1680	120	1688	120
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1920	130	1928	130
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	1990	140	1998	140
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2010	150	2018	150
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2430	150	2438	150
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2580	160	2588	160
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2620	180	2628	180
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2730	200	2738	200
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2760	180	2768	180
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2820	180	2828	180
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2910	190	2918	190
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	2940	200	2948	200
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	3250	200	3258	200
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	3590	220	3598	220

Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	3800	230	3808	230
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	3820	240	3828	240
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	4090	250	4098	250
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	5310	350	5318	350
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	6180	370	6188	370
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	8430	510	8438	510
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	L	2004	13110	800	13118	800
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	R	1950	980	55	933	109
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	R	1950	1380	35	1369	46
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	R	1950	2820	35	3004	97
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	R	1950	2910	60	3142	163
Nebraska	Nebraska Sand Hills	Goble et al. 2004	2004	R	1950	4150	40	4761	130
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2004	180	10	188	10
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	810	60	822	60
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	860	60	872	60
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	910	70	922	70
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	930	70	942	70
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	950	70	962	70
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	2360	160	2372	160

Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	2400	250	2412	250
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	3360	230	3372	230
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	L	2000	3900	270	3912	270
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	490	50	574	51
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	525	40	595	29
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	625	50	667	63
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	700	45	739	48
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	715	30	734	27
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	750	30	758	32
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	770	90	793	105
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	770	70	779	84
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	790	35	780	48
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	790	30	769	36
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	820	50	797	66
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	820	30	796	50
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	840	30	802	55
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	840	30	802	55
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	840	35	802	58
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	865	36	810	56

Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	865	35	810	55
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	875	80	865	125
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	885	30	845	51
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	910	50	892	97
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	910	50	892	97
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	910	30	900	78
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	915	35	902	80
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	920	40	903	82
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	925	35	907	80
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	925	30	911	76
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	930	30	916	72
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	930	40	907	82
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	930	30	916	72
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	930	50	897	95
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	935	30	918	69
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	940	35	917	75
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	940	30	920	67
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	940	30	920	67
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	945	35	920	73

Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	950	35	921	71
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	950	30	922	66
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	960	50	924	98
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	960	35	924	71
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	960	30	904	47
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	965	50	926	99
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	965	35	925	73
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	970	30	904	47
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	970	45	935	90
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	980	55	933	109
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	990	45	945	94
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	990	35	989	36
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	995	30	993	33
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1010	30	1001	38
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1020	50	1014	61
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1020	35	1006	44
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1040	120	1018	229
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1070	40	1055	66
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1090	30	1066	53

Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1130	45	1117	99
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	1380	35	1369	46
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	2820	35	3004	97
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	2910	60	3142	163
Nebraska	Nebraska Sand Hills	Mason et al. 2004	2004	R	1950	4150	40	4761	130
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	40	10	52	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	60	10	72	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	70	10	82	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	70	10	82	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	75	15	87	15
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	80	10	92	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	100	10	112	10
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	140	20	152	20
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	196	89	208	89
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	240	40	252	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	400	50	412	50

Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	420	40	432	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	430	40	442	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	450	50	462	50
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	450	40	462	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	460	40	472	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	480	40	492	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	480	30	492	30
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	480	30	492	30
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	520	40	532	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	520	40	532	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	540	40	552	40
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	660	50	672	50
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	670	90	682	90
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	690	70	702	70

Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	1250	100	1262	100
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	1430	120	1442	120
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	1480	160	1492	160
Nebraska	Nebraska Sand Hills	Forman et al. 2005	2005	L	2000	1490	160	1502	160
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	500	40	505	40
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	620	70	625	70
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	620	100	625	100
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	630	90	635	90
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	630	100	635	100
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	690	100	695	100
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	690	50	695	50
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	720	100	725	100
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	760	130	765	130
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	800	75	805	75
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	830	50	835	50
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	830	130	835	130
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	850	90	855	90
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	870	110	875	110

Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	880	70	885	70
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	890	130	895	130
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	920	110	925	110
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	960	140	965	140
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	980	70	985	70
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	1060	70	1065	70
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	1100	70	1105	70
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2400	180	2405	180
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2480	260	2485	260
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2480	150	2485	150
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2570	180	2575	180
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2750	310	2755	310
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2810	300	2815	300
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	2830	180	2835	180
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	3160	190	3165	190
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	3220	310	3225	310
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	3260	180	3265	180
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	3870	340	3875	340
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	4340	240	4345	240

Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	4400	450	4405	450
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	4480	270	4485	270
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	4600	450	4605	450
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	5650	370	5655	370
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	7540	850	7545	850
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	7725	510	7730	510
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	7820	590	7825	590
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	7890	715	7895	715
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	7990	690	7995	690
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	8150	590	8155	590
Nebraska	Nebraska Sand Hills	Miao et al. 2007	2007	L	2007	9010	630	9015	630
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	490	50	491	50
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	540	50	541	50
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	680	50	681	50
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	700	60	701	60
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	710	90	711	90
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	740	60	741	60
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	1480	120	1481	120
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	2100	200	2101	200

Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	2500	200	2501	200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	2800	200	2801	200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	3000	200	3001	200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	7500	500	7501	500
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	9600	1000	9601	1000
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	10700	700	10701	700
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	12900	700	12901	700
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	13500	1100	13501	1100
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	13600	1000	13601	1000
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	13700	1000	13701	1000
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	14100	1200	14101	1200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	14100	1200	14101	1200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	14700	1200	14701	1200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	14700	1400	14701	1400
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	14900	1400	14901	1400
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15100	1300	15101	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15400	1300	15401	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15500	1300	15501	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15500	1400	15501	1400

Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15600	1300	15601	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15700	1300	15701	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	15700	1200	15701	1200
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	16200	1300	16201	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	16300	1300	16301	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	16800	1300	16801	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	17000	1300	17001	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	17300	1300	17301	1300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	18500	2300	18501	2300
Nebraska	Nebraska Sand Hills	Mason et al. 2011	2011	L	2011	18700	1800	18701	1800
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	628	37	629	37
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	2664	142	2665	142
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	774	50	775	50
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	788	61	789	61
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	853	46	854	46
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	868	47	867	47
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	3411	217	3412	217

Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	3951	25	3952	25
Nebraska	Nebraska Sand Hills	Schmieder et al. 2011	2011	L	2011	668	44	669	44
Nebraska	Wray dunes	Forman et al. 2005	2005	L	2000	70	10	82	10
Nebraska	Wray dunes	Forman et al. 2005	2005	L	2000	80	10	92	10
Nebraska	Wray dunes	Forman et al. 2005	2005	L	2000	420	30	432	30
Nebraska	Wray dunes	Forman et al. 2005	2005	L	2000	540	40	552	40

a Dating method: L = Luminescence; R = Radiocarbon. See Chapter 2 for specific dating technique.

b Age Datum: 1950 is assumed for all ^{14}C ages; date of publication is assumed as the age datum for all luminescence samples unless otherwise reported by the original authors.

c Age and Error: As originally reported (see Chapter 2 for details).

d Calibrated Age: Calibrated to "years before" AD 2012.

e Calibrated Error: All ^{14}C ages are shown with 2σ errors; all luminescence ages are shown with their original σ error (see Chapter 2 for details).

AI.4. Southern U.S. Great Plains

Province	Dune Field	Study	Yr.	M[a]	Age Dat[b]	Age[c]	± Er.[c]	Cal. Age[d]	Cal. ± Er.[e]
New Mexico	Auxiliary Field	Holliday 2001	2001	R	1950	7715	60	8562	95
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	7880	185	8821	396
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	10660	245	12517	652
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	13730	130	16913	302
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	14740	120	17920	296
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	15150	150	18393	341
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	16210	510	19563	1017
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	21540	220	25751	650
New Mexico	High Plains lunettes	Holliday 1997	1997	R	1950	21865	305	26167	950
New Mexico	Lea-Yoakum dunes	Holliday 2001	2001	R	1950	3475	100	3792	254
New Mexico	Lea-Yoakum dunes	Holliday 2001	2001	R	1950	4720	325	5440	805
New Mexico	Lea-Yoakum dunes	Holliday 2001	2001	R	1950	6130	165	7056	343
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	680	80	696	108
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	910	100	889	158
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	1480	160	1458	341
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	1480	60	1433	77
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	2500	60	2648	154
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	3800	60	4304	169

New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	3890	60	4358	148
New Mexico	Muleshoe dunes	Holliday 2001	2001	R	1950	4855	90	5660	154
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	460	40	467	40
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	500	70	507	70
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	630	70	637	70
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	670	130	677	130
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	720	120	727	120
Oklahoma	Cimarron Bend dunes	Werner et al. 2011	2011	L	2005	810	90	817	90
Oklahoma	Cimarron River Valley dunes	Cordova et al. 2005	2005	L	2005	213	23	220	23
Oklahoma	Cimarron River Valley dunes	Cordova et al. 2005	2005	R	1950	2900	40	3346	120
Oklahoma	Cimarron River Valley dunes	Cordova et al. 2005	2005	R	1950	5690	50	6577	120
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	770	40	777	40
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	800	50	807	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	810	40	817	40

Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	830	50	837	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	830	50	837	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	870	50	877	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	870	50	877	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	880	50	887	50
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	L	2005	3330	180	3337	180
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	R	1950	1110	40	1073	79
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	R	1950	1570	40	1520	83
Oklahoma	Cimarron River Valley dunes	Lepper and Scott 2005	2005	R	1950	10207	40	11976	153
Texas	Andrew dunes	Holliday 2001	2001	R	1950	2340	40	2459	91
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	450	30	566	32
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	755	35	759	36
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	850	60	819	78

Texas	High Plains lunettes	Holliday 1997	1997	R	1950	1000	85	967	178
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	1335	75	1283	149
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	3110	45	3374	97
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	5500	65	6361	117
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	6115	190	7071	412
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	6695	80	7616	118
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	6980	215	7879	384
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	7250	50	8135	97
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	7965	170	8914	428
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	8030	65	8902	195
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	8320	90	9351	206
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	9470	70	10781	168
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	11670	80	13598	200
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	12080	200	14125	608
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	13800	90	16986	212
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	14940	240	18185	532
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	15040	200	18289	439
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	19320	750	23191	1801
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	19340	825	23150	2027
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	24410	1280	28788	2551

Texas	High Plains lunettes	Holliday 1997	1997	R	1950	29080	1030	33390	2021
Texas	High Plains lunettes	Holliday 1997	1997	R	1950	33750	3600	37895	6512
Texas	Lea-Yoakum dunes	Holliday 2001	2001	R	1950	3215	355	3619	861
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	645	150	734	244
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	720	195	780	297
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	4120	210	4650	505
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	6240	260	7120	528
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	7125	190	8034	356
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	7330	245	8196	474
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	7630	485	8616	995
Texas	Muleshoe dunes	Holliday 2001	2001	R	1950	14275	585	17202	1539
Texas	Red Lake	Holliday 2001	2001	R	1950	1680	65	1631	159
Texas	Red Lake	Holliday 2001	2001	R	1950	1810	70	1785	161
Texas	Red Lake	Holliday 2001	2001	R	1950	8470	220	9639	598
Texas	Red Lake	Holliday 2001	2001	R	1950	8640	160	9851	390
Texas	Red Lake lunette	Holliday 2001	2001	R	1950	10050	170	11762	520
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	30	5	42	5
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	95	10	107	10
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	195	20	207	20

Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	200	20	212	20
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	210	20	222	20
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	255	40	267	40
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	1235	85	1247	85
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	1420	150	1432	150
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	1955	150	1967	150
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	2130	190	2142	190
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	2680	225	2692	225
Texas	South Texas sand sheet	Forman et al. 2009	2009	L	2000	2730	220	2742	220
Texas	Terry County	Holliday 2001	2001	R	1950	255	60	434	116

a Dating method: L = Luminescence; R = Radiocarbon. See Chapter 2 for specific dating technique.

b Age Datum: 1950 is assumed for all ^{14}C ages; date of publication is assumed as the age datum for all luminescence samples unless otherwise reported by the original authors.

c Age and Error: As originally reported (see Chapter 2 for details).

d Calibrated Age: Calibrated to "years before" AD 2012.

e Calibrated Error: All ^{14}C ages are shown with 2σ errors; all luminescence ages are shown with their original σ error (see Chapter 2 for details).

Appendix II

LATITUDE AND LONGITUDE COORDINATES FOR DUNE FIELDS FOUND WITHIN THE GREAT PLAINS

Center point latitude and longitude coordinates of Great Plains dune fields. Citations are provided if the dune field has been studied for chronological data.

Canadian Great Plains Dune Fields

Battle River Sand Hills; Wolfe et al. (2004)

52.56446 N, -113.55233 W

Bear River Sand Hills; Wolfe et al. (2004)

55.09980 N, -118.64009 W

Beaverhill Creek Sand Hills; Wolfe et al. (2004)

53.84838 N, -112.97160 W

Chisholm Sand Hills; Wolfe et al. (2004)

54.82386 N, -114.18203 W

Decrene Sand Hills; Wolfe et al. (2004)

55.10647 N, -114.15047 W

Duchess Sand Hills; Wolfe et al. (2002b)

50.87407 N, -111.85680 W

Economy Creek Sand Hills; Wolfe et al. (2004)

55.06323 N, -118.19649 W

Edson Sand Hills; Wolfe et al. (2004)

53.49483 N, -116.62900 W

Fort Assiniboine Sand Hills; Wolfe et al. (2004)

54.45155 N, -114.50479 W

Grovedale Sand Hills; Wolfe et al. (2004)
55.03705 N, -118.75084 W

High Level Dunes; Wolfe et al. (2007b)
58.36828 N, -116.40294 W

Holmes Crossing Sand Hills; Wolfe et al. (2004)
54.27939 N, -114.84759 W

Hondo Sand Hills; Wolfe et al. (2004)
55.00393 N, -114.07005 W

Lac La Biche Sand Hills; Wolfe et al. (2004)
54.96980 N, -112.11579 W

Lodgepole Sand Hills; Wolfe et al. (2004)
53.12339 N, -115.21520 W

Nelson Lake Sand Hills; Wolfe et al. (2004)
54.52165 N, -114.25369 W

Pipestone Sand Hills; Wolfe et al. (2004)
54.99890 N, -119.19560 W

Redstone Sand Hills; Wolfe et al. (2004)
53.93063 N, -112.96194 W

Rocky Mountain House Sand Hills; Wolfe et al. (2004)
52.39991 N, -114.98886 W

Stony Plain Sand Hills; Wolfe et al. (2004)
53.42852 N, -113.77753 W

Watino Sand Hills; Wolfe et al. (2004)
55.58800 N, -117.53711 W

Windfall Sand Hills; Wolfe et al. (2004)
54.19101 N, -116.11291 W

Brandon Sand Hills; David (1971); Wolfe et al. (2000); Wolfe et al. (2002a)
49.74808 N, -99.28702 W

Bigstick Sand Hills; Wolfe et al. (2001)
50.19006 N, -109.16284 W

Burstall Sand Hills; Wolfe et al. (2001)
50.14873 N, -109.85702 W

Dundurn Sand Hills; Turchenek et al. (1974); Lian et al. (2002)
51.85457 N, -106.60102 W

U.S. Great Plains Dune Fields

Winnibigoshish dunes; Grigal et al. (1976)
47.35284 N, -94.07962 W

Minot dunes; Muhs et al. (1997)
48.36142 N, -100.44473 W

Sheyenne Delta dunes; Running (1995); Running (1996)
46.41599 N, -97.24162 W

White River Badlands sand dunes; Rawling et al. (2003)
43.63240 N, -102.34242 W

Casper dunes; Albanese (1974); Halfen et al. (2010)
42.97535 N, -105.97206 W

Ferris dunes; Gaylord (1982); Gaylord (1990); Stokes and Gaylord (1993)
42.12514 N, -107.15923 W

Fort Morgan dunes; Forman et al. (1992); Madole (1994); Forman et al. (1995); Madole (1995); Clarke and Rendell (2003)
40.27972 N, -103.29533 W

Hudson dunes; Forman and Maat (1990)
40.18813 N, -104.53755 W

Greeley dunes; Forman et al. (1992)
40.44459 N, -103.60774 W

North Park dunes; Ahlbrandt et al. (1983)
40.82160 N, -106.11046 W

Green River Lowlands; Miao et al. (2010)
41.51039 N, -90.15156 W

Abilene Dunes; Hanson et al. (2010)
38.92035 N, -97.28147 W

Hutchinson Dunes; Halfen et al. (2012)
38.12923 N, -97.83750 W

Arkansas River Dunes; Forman et al. (2008)
37.91736 N, -101.38937 W

Cimarron Bend Dunes; Olsen and Porter (2002); Werner et al. (2011)
37.27701 N, -101.25483 W

Great Bend Sand Prairie; Arbogast (1996); Arbogast and Johnson (1998)
37.95073 N, -98.76202 W

Duncan Dunes; Hanson et al. (2009)
41.37701 N, -97.62789 W

Nebraska Sand Hills; Ahlbrandt et al. (1983); Loope et al. (1995); Stokes and; Swinehart (1997); Goble et al. (2004); Mason et al. (2004); Forman et al. (2005); Miao et al. (2007); Schmieder et al. (2011)
41.97708 N, -100.97789 W

Wray Dunes; Forman et al. (2005)
40.04278 N, -102.36634 W

Imperial Dunes
40.68118 N, -101.62241 W

Lincoln County Dunes
40.91902 N, -100.99413 W

Big Sandy Creek Dunes
38.70519 N, -102.92537 W

Black Squirrel Creek Dunes
38.562569 N, -104.24154 W

Ute Creek Dunes
35.44107 N, -103.00309 W

Muleshoe Dunes; Holliday (2001)
34.14795 N, -102.97015 W

Lea-Yoakum Dunes; Holliday (2001)
33.36461 N, -102.69764 W

Mescalero Dunes
32.74294 N, -103.81024 W

Monahans Dunes; Holliday (2001)
31.66655 N, -102.86485 W

Andrews Dunes; Holliday (2001)
32.08838 N, -102.94730 W

Crosby Dunes
33.50016 N, -101.46999 W

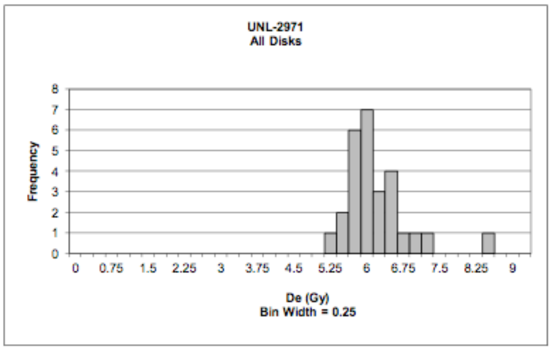
Hemphill County Dunes
35.94875 N, -100.19070 W

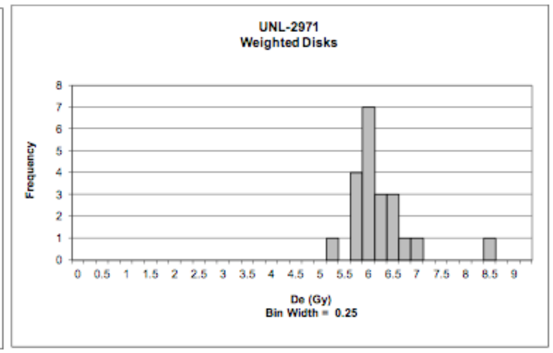
Cimarron Valley Dunes; Cordova et al. (2005); Lepper and Scott (2005)
36.50615 N, -98.88915 W

South Texas Sand Sheet; Forman et al. (2009)
27.12659 N, -97.66658 W

Appendix III

REPRESENTATIVE D_E DISTRIBUTIONS, OSL GROWTH CURVES, AND NATURAL SHINE-DOWN CURVES FOR OSL SAMPLES FROM THE HUTCHINSON DUNES





All Disks

	De (Gy)	Age (ka)
Mean =	6.16	2.120
Median =	5.87	2.018
Min =	5.14	1.768
Max =	9.50	3.268

S.D. (1σ) =	0.91	
Std. Error =	0.17	
Error Median =	0.32	
n =	28	Discs

Disc	De	Error	Wt
1	5.783	0.13	1
2	5.580	0.67	1
3	5.590	0.32	1
4	5.378	0.50	1
5	5.632	0.47	1
6	5.936	0.23	1
7	6.001	0.15	1
8	5.881	0.97	1
9	7.023	0.53	1
10	5.692	0.49	1
11	6.805	0.31	1
12	6.441	0.48	1
13	5.805	0.18	1
14	5.699	0.37	1
15	5.578	0.16	1
16	5.821	0.72	1
17	6.604	0.23	1
18	9.497	0.44	1
19	6.052	0.36	1
20	6.393	0.16	1
21	5.334	0.46	1
22	8.349	0.40	1
23	5.139	0.08	1
24	5.849	0.00	1
25	6.106	0.28	1
26	6.278	0.10	1
27	5.840	0.07	1
28	6.440	0.07	1
29			
30			
31			
32			
33			
34			
35			

Weighted Disks

	De (Gy)	Age (ka)	Total Errors +/- 1σ	+/- 1 Std. Err
Mean =	5.96	2.051	0.229	0.188
Median =	5.87	2.018		
Min =	5.14	1.768		
Max =	6.80	2.341		

S.D. (1σ) =	0.39	
Std. Error (1σs)=	0.09	
Error Median =	0.20	
n =	20	Discs

Disc	De	Error	Wt
1	5.783	0.13	1
2	5.590	0.32	1
3	5.632	0.47	1
4	5.936	0.23	1
5	6.001	0.15	1
6	5.881	0.97	1
7	6.805	0.31	1
8	5.805	0.18	1
9	5.699	0.37	1
10	5.578	0.16	1
11	5.821	0.72	1
12	6.604	0.23	1
13	6.052	0.36	1
14	6.393	0.16	1
15	5.139	0.08	1
16	5.849	0.00	1
17	6.106	0.28	1
18	6.278	0.10	1
19	5.840	0.07	1
20	6.440	0.07	1
21			
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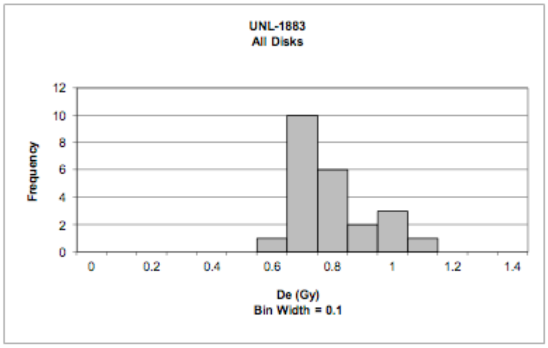

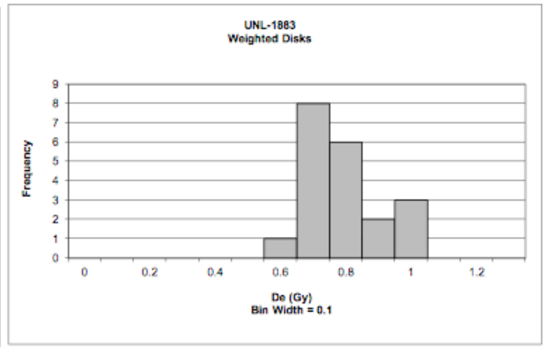

All Disks

	De (Gy)	Age (ka)
Mean =	**0.75**	**0.302**
Median =	0.75	0.300
Min =	0.60	0.240
Max =	1.02	0.409

S.D. (1σ) =	0.11	
Std. Error =	0.02	
Error Median =	0.08	
n =	23	Discs

Weighted Disks

	De (Gy)	Age (ka)
Mean =	**0.75**	**0.301**
Median =	0.75	0.300
Min =	0.60	0.240
Max =	0.95	0.381

S.D. (1σ) =	0.10	
Std. Error (1σs)=	0.02	
Error Median =	0.07	
n =	20	Discs

Total Errors

+/- 1σ	+/- 1 Std. Err
0.046	**0.025**

Disc	De	Error	Wt	Age	+/- 1 σ
1	0.664	0.06	1	0.267	0.84
2	0.597	0.13	1	0.240	1.51
3	0.630	0.10	1	0.253	1.18
4	0.947	0.14	1	0.381	1.98
5	0.695	0.04	1	0.279	0.54
6	0.677	0.07	1	0.272	0.71
7	0.659	0.08	1	0.265	0.89
8	0.842	0.06	1	0.338	0.93
9	0.657	0.06	1	0.264	0.91
10	0.803	0.02	1	0.323	0.54
11	0.931	0.09	1	0.374	1.82
12	0.752	0.02	1	0.302	0.03
13	0.770	0.07	1	0.309	0.21
14	0.746	0.04	1	0.300	0.03
15	1.017	0.12	1	0.409	2.67
16	0.747	0.14	1	0.300	0.02
17	0.934	0.07	1	0.375	1.84
18	0.776	0.10	1	0.312	0.27
19	0.664	0.10	1	0.267	0.84
20	0.664	0.02	1	0.267	0.84
21	0.754	0.38	1	0.303	0.05
22	0.695	0.26	1	0.279	0.53
23	0.649	0.20	1	0.261	1.00
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					

Disc	De	Error	Wt	Age	+/- 1 σ
1	0.664	0.06	1	0.267	0.84
2	0.597	0.13	1	0.240	1.51
3	0.947	0.14	1	0.381	1.98
4	0.695	0.04	1	0.279	0.54
5	0.677	0.07	1	0.272	0.71
6	0.659	0.08	1	0.265	0.89
7	0.842	0.06	1	0.338	0.93
8	0.657	0.06	1	0.264	0.91
9	0.803	0.02	1	0.323	0.54
10	0.931	0.09	1	0.374	1.82
11	0.752	0.02	1	0.302	0.03
12	0.770	0.07	1	0.309	0.21
13	0.746	0.04	1	0.300	0.03
14	0.747	0.14	1	0.300	0.02
15	0.934	0.07	1	0.375	1.84
16	0.776	0.10	1	0.312	0.27
17	0.664	0.10	1	0.267	0.84
18	0.664	0.02	1	0.267	0.84
19	0.754	0.38	1	0.303	0.05
20	0.695	0.26	1	0.279	0.53
21					
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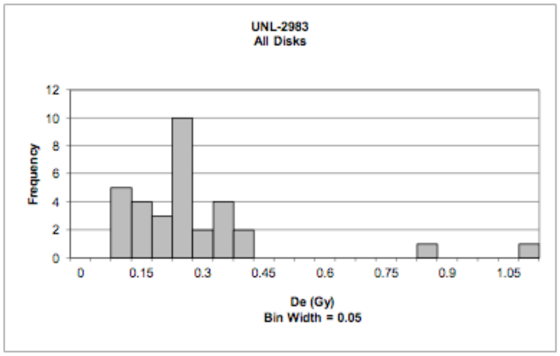

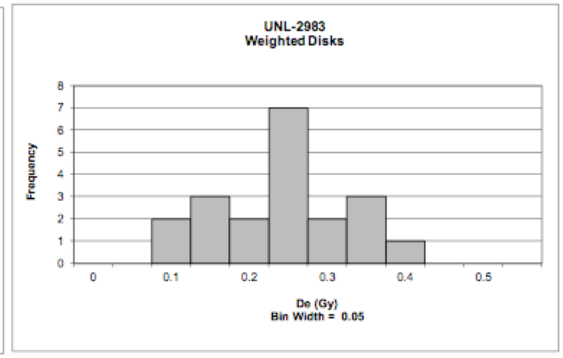

All Disks

	De (Gy)	Age (ka)
Mean =	**0.54**	**0.218**
Median =	0.22	0.090
Min =	0.05	0.022
Max =	10.04	4.053

S.D. (1σ) =	1.74	
Std. Error =	0.31	
Error Median =	0.15	
n =	32	Discs

Weighted Disks

	De (Gy)	Age (ka)
Mean =	**0.22**	**0.090**
Median =	0.22	0.090
Min =	0.10	0.039
Max =	0.36	0.144

S.D. (1σ) =	0.08	
Std. Error (1σs)=	0.02	
Error Median =	0.10	
n =	20	Discs

Total Errors

+/- 1σ	+/- 1 Std. Err
0.033	**0.011**

Disc	De	Error	Wt	Age	+/- 1 σ
1	0.804	0.41	1	0.324	7.43
2	0.224	0.11	1	0.090	0.02
3	0.248	0.16	1	0.100	0.32
4	0.196	0.14	1	0.079	0.34
5	0.344	0.28	1	0.139	1.55
6	0.229	0.10	1	0.092	0.08
7	0.204	0.03	1	0.082	0.24
8	0.338	0.13	1	0.136	1.47
9	0.342	0.05	1	0.138	1.52
10	0.249	0.23	1	0.101	0.34
11	0.096	0.11	1	0.039	1.62
12	0.304	0.31	1	0.123	1.04
13	0.198	0.38	1	0.080	0.31
14	0.054	0.42	1	0.022	2.15
15	0.138	0.25	1	0.056	1.09
16	0.212	0.36	1	0.086	0.13
17	0.098	0.08	1	0.039	1.60
18	0.240	0.27	1	0.097	0.22
19	0.356	0.19	1	0.144	1.71
20	0.133	0.15	1	0.054	1.14
21	10.041	0.20	1	4.053	125.55
22	0.387	0.39	1	0.156	2.10
23	0.066	0.37	1	0.027	2.00
24	0.091	0.75	1	0.037	1.69
25	0.235	0.01	1	0.095	0.16
26	0.119	0.05	1	0.048	1.32
27	0.198	0.09	1	0.080	0.32
28	0.147	0.15	1	0.059	0.97
29	0.276	0.03	1	0.111	0.68
30	0.221	0.00	1	0.089	0.02
31	0.207	0.05	1	0.084	0.20
32	0.268	0.04	1	0.108	0.58
33					
34					
35					

Disc	De	Error	Wt	Age	+/- 1 σ
1	0.224	0.11	1	0.090	0.02
2	0.248	0.16	1	0.100	0.32
3	0.196	0.14	1	0.079	0.34
4	0.229	0.10	1	0.092	0.08
5	0.204	0.03	1	0.082	0.24
6	0.338	0.13	1	0.136	1.47
7	0.342	0.05	1	0.138	1.52
8	0.249	0.23	1	0.101	0.34
9	0.096	0.11	1	0.039	1.62
10	0.304	0.31	1	0.123	1.04
11	0.098	0.08	1	0.039	1.60
12	0.356	0.19	1	0.144	1.71
13	0.133	0.15	1	0.054	1.14
14	0.119	0.05	1	0.048	1.32
15	0.198	0.09	1	0.080	0.32
16	0.147	0.15	1	0.059	0.97
17	0.276	0.03	1	0.111	0.68
18	0.221	0.00	1	0.089	0.02
19	0.207	0.05	1	0.084	0.20
20	0.268	0.04	1	0.108	0.58
21					
22					
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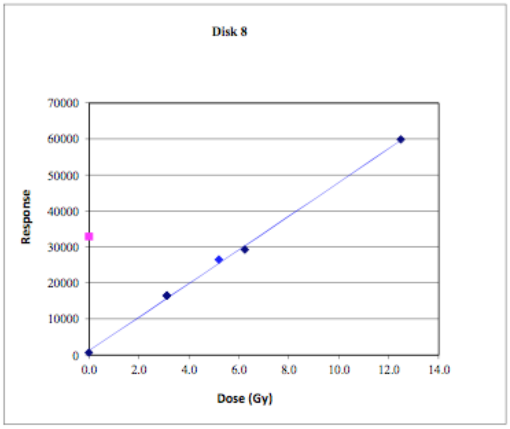
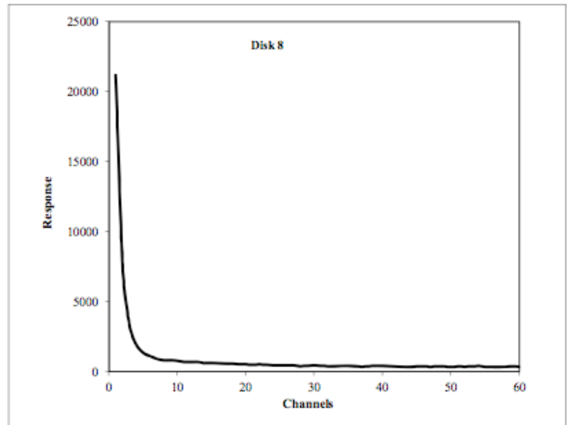
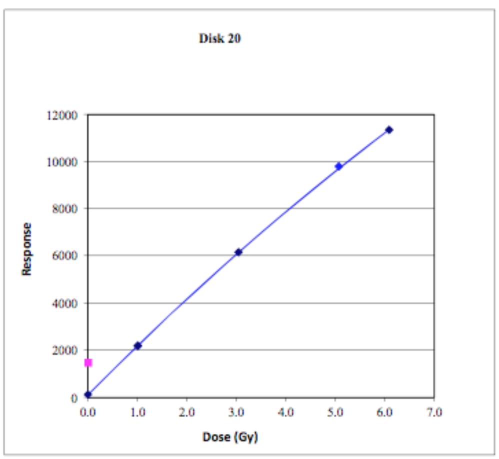
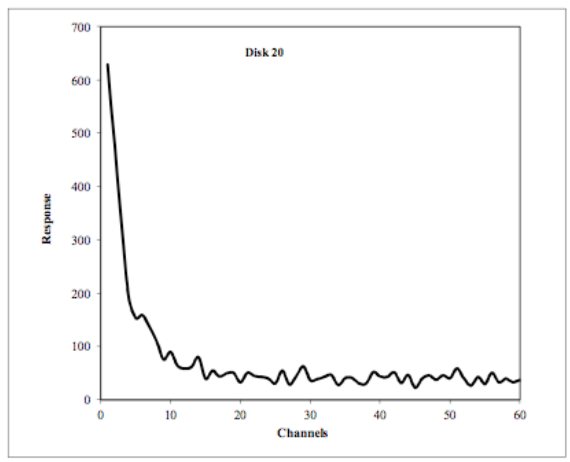
Sample UNL-2971 Representative OSL Growth Curve and Natural Shinedown



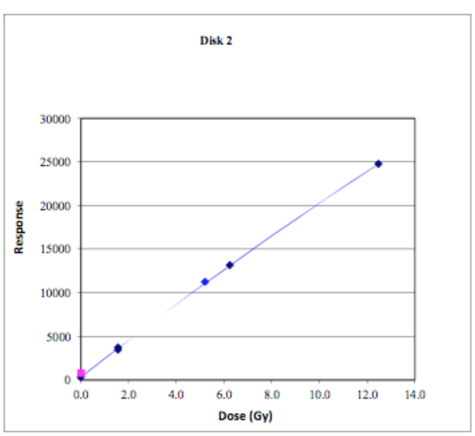


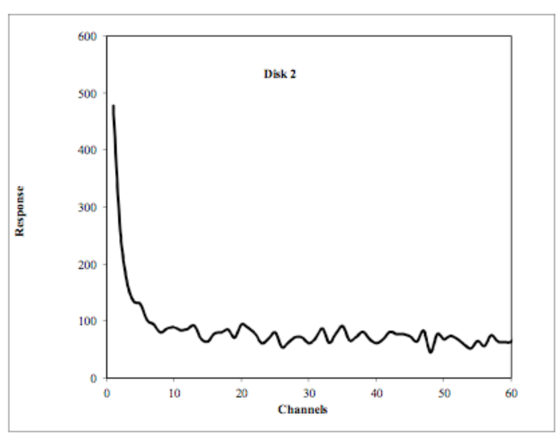
Sample UNL-1883 Representative OSL Growth Curve and Natural Shinedown





Sample UNL-2983 Representative OSL Growth Curve and Natural Shinedown





Appendix IV

DETAILED SOIL DESCRIPTIONS OF THE ROBINSON TRACT SITES (KANSAS RIVER DUNES)

Sample Pit	Horizon	Depth (cm)	Bnd.[a]	Color Wet	Color Dry	Texture[b]	Structure[c]	Moist Const.[d]	Ped/Void Surface[e]	Roots[f]	Pores[g]	Efferv.[h]
RT-1												
	A	22	cs	10YR 2/2	10YR 4/1	s	1f, mgr, sg	vfrsopo		2, 3vf, ft	2, 3vf, fdt, 2fig	ne
	Bt1	39	ci	10YR 3/3	7.5YR 4/3	scl	1m, cosbk	frsssp	vf 10YR 5/1 brfddb	1, 2vf, ft	1, 2vfdt	ne
	Bt2	59	gs	10YR 4/3	7.5YR 4/4	scl	1f, m, cosbk	frsssp	vf 10YR 5/2 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne
	Bw	80	ds	10YR 4/4	7.5YR 4/3	sc	1f, m, cosbk	frsssp		1, 2vf, ft	2vfdt, 2vfig	ne
	C	105		10YR 4/4	7.5YR 5/3	cos	sg	lsopo		1vf, ft	ir	ne
RT-2												
	A	27	cw	10YR 2/1	7.5YR 4/1	s	1f, mgr, sg	vfrsopo		2, 3vf, ft	1, 3vf, fdt, ir	ne
	A2	86	gs	10YR 2/1	7.5YR 3/1	s	1f, mgr	vfrsopo		2, 3vf, ft	1, 2vfdt, 1fig	ne
	AB	106	gs	10YR 2/2	7.5YR 4/2	s	1fsbk	vfrsopo		2, 3vf, ft	2vfdt, 2vfig	ne
	Bt1	130	gs	10YR 3/3	7.5YR 5/3	scl	1f, msbk	fisssp	vf 10YR 5/2 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne
	Bt2	150		10YR 4/4	7.5YR 4/3	scl	1f, msbk	fisssp	vf 10YR 5/2 brfddb	1vft	1vfdt, 1vfig	ne
RT-3												
	A	23	cs	10YR 3/1	7.5YR 4/2	s	1f, mgr, sg	vfrsopo		3vft	1, 2vfdt, 2vfig	ne
	AB	53	cs	10YR 3/3	7.5YR 4/3	s	1fsbk	vfrsopo		1, 2vf, ft	2vfdt, 2vfig	ne
	Bt1	80	gs	10YR 4/4	7.5YR 5/4	scl	1f, msbk	frsosp	vf 10YR 5/1 brfddb	1vf, ft	2vfdt, 2vfig	ne
	Bt2	110		10YR 4/3	7.5 6/3	scl	1f, msbk	fisssp	vf 10YR 5/1 brfddb	1vf, ft	1vfdt, 1vfig	ne
RT-4												
	A	28	gi	10YR 2/2	7.5YR 3/2	s	1f, mgr, sg	vfrsopo		3vft	1, 3vf, fdt, ir	ne
	Bt1	45	cs	10YR 2/2	7.5YR 4/2	scl	1f, msbk	frsosp	vf 10YR 5/1 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne
	Bt2	56	as	10YR 3/3	7.5YR 4/3	scl	1f, msbk	fisssp	vf 10YR 5/2 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne
	2C	68		10YR 3/4	7.5YR 5/6	c	3m, cosbk	vfisssp	f2pfmctotfis	1vft	1vfdt, 1vfig	ne
RT-5												
	A	15	gs	10YR 2/2	7.5YR 4/2	s	1f, mgr, sg	vfrsopo		3vft	2vfdt, 2vfig	ne
	AB	30	cs	10YR 3/2	7.5YR 4/2	s	1fsbk	vfrsopo		1, 2vf, ft	2vfdt, 2vfig	ne
	Bt1	47	gs	7.5YR 3/3	7.5YR 4/4	scl	1f, msbk	vfrsosp	vf 10YR 5/1 brfddb	1, 2vf, ft	2, 3vf, cdt, 2vfig	ne
	Bt2	75	gs	7.5YR 4/4	7.5YR 4/6	scl	1f, msbk	vfrsssp	vf 10YR 5/2 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne
	C	110		7.5YR 5/6	7.5YR 5/4	cos	sg	lsopo		1vft	ir	ne
RT-6												
	A	50	cw	10YR 2/1	7.5YR 3/1	s	1f, mgr, sg	vfrsopo		1, 3vf, ft	1, 3vf, fdt, ir	ne
	AB	83	gs	10YR 2/1	7.5YR 4/2	s	1fsbk	vfrsopo		1, 2vf, ft	2vfdt, 2vfig	ne
	Bt	110		10YR 3/2	7.5YR 5/2	scl	1f, msbk	frsssp	vf 10YR 5/2 brfddb	1, 2vf, ft	2vfdt, 2vfig	ne

[a] Bnd.,Boundary; c, clear; g, gradual; d, diffuse; a, abrupt; s, smooth; i, irregular; w, wavy.
[b] s, sand; scl, sandy clay loam; cos, coarse sand; c, clay.
[c] 1=Weak; 3=Strong; f, fine; m, medium; co, coarse; gr, granular; sbk, sub-angular blocky; sg, single grain.
[d] vfr, very friable; fr, friable; fi, firm; l, loose; so, non-sticky; ss, slightly sticky; po, non-plastic; sp, slightly plastic.
[e] vf, very fine; brf, clay bridges; d, diffuse; d, distinct; b, between sand grains; f, few; 2=Medium; p, prominent; fmc, iron-manganese; tot, throughout; fi, firm; s, smooth.
[f] 1=Few; 2=Common; 3=Many; vf, very fine; f, fine; t, throughout.
[g] 1=Few; 2=Common; 3=Many; vf, very fine; f, fine; dt, dendritic tubular; ig, irregular; ir, interstitial.
[h] Efferv., Effervescence; ne, non-effervescence.

ALAN FREDERICK HALFEN

Curriculum Vitae

University of Kansas, Department of Geography
207 Lindley Hall, 1475 Jayhawk Blvd., Lawrence, Kansas 66045 USA
cell (847) 951-8990 • office (785) 864-5538 • fax (785) 864-5378
afhalfen@ku.edu • www.people.ku.edu~afhalfen

November 2012

RESEARCH SPECIALTIES

Quaternary Landscapes and Climate Change: Landscape and landform response to Quaternary climate change, especially that of the Great Plains and upper Midwest.

Optically Stimulated Luminescence Dating: Laboratory techniques and applications for dating Quaternary sediments using optical stimulated luminescence.

Aeolian Geomorphology**:** Modern and prehistoric formation, modification, and morphology of sand dunes and sand seas, especially Quaternary dune fields of the North American Great Plains.

EDUCATION

Doctor of Philosophy (*12/12*) Adv: William C. Johnson, Ph.D.	Department of Geography, University of Kansas Dissertation: *Aeolian dune fields of Kansas and their response to late-Quaternary megadroughts* (defended 4/11/12)
Master of Science (*05/07*) Adv: Glen G. Fredlund, Ph.D.	Dept. of Geography, U. of Wisconsin–Milwaukee Thesis: *Late-Quaternary chronology and stratigraphy of the Casper Dune Field, Casper, Wyoming, USA.*
Bachelor of Science (*05/05*) Adv: J. Elmo Rawling III, Ph.D.	Dept. of Geography, U. of Wisconsin–Platteville Major: *Geography – Physical geography emphasis*

ACADEMIC APPOINTMENTS

08/08 – 07/12	Department of Geography, University of Kansas	Lecturer
01/09 – 05/09	Department of Geography, University of Kansas	Lab Instructor
01/08 – 06/08	Department of Geography and Earth Sciences, Carthage College	Adjunct Faculty
08/05 – 05/08	Dept. of Geography, U. of Wisconsin-Milwaukee	Lab Instructor

FUNDED RESEARCH EXPERIENCE

01/11 – Present — NSF-funded research: "Evaluating the Potential of Stereoscopic Display for Geographic Education" *Awarded to T. Slocum, S. Egbert, and W.C. Johnson*.

Activities: *Manage research project while primary PI (Slocum) is on sabbatical; Assist in the implementation of equipment and technology; Develop 3-D teaching materials, lesson plans, and student assessments; Instruct students in classes associated with project*.

05/10 – Present — United States Geological Survey Education Mapping Project: "Geologic mapping and stratigraphic characterization of alluvial landforms within the Kansas River valley" and facsimile. *Awarded to W.C. Johnson: FY 2010, 2011, & 2012*.

Activities: *Supervise undergraduate students (unofficial for FY 2011 & 2012); Geological mapping and stratigraphic analysis Laboratory analysis of collected samples*.

AWARDS AND FELLOWSHIPS

08/11 — Poster Award for "Medieval Climatic Anomaly and Little Ice Age dune activity in the Arkansas River valley, Central Great Plains, USA" at 18th congress of the International Union for Quaternary Research, Bern, Switzerland. *Sponsored by Nature Geoscience*.

04/11 — University of Kansas Outstanding Graduate Teaching Assistant Award.

12/10 — *BIOone*-featured article, *PALAIOS*: "Traces and burrowing behaviors of the western harvester ant *Pogonomymrex occidentalis*: paleopedogenic and paleoecological significance".

08/10 — U.S. National Committee of Soil Science Wilford R. Gardner Fellowship.

10/09 — Runner-up best student paper for "Significance of the western harvester ant in soil bioturbation and pedological development: results of neoichnology experiments" at the Soil Science Society of America International Conference, Pittsburgh, PA, USA.

08/08 — University of Kansas, Department of Geography Fellowship.

08/07 — University of Wisconsin-Milwaukee, Mary Jo Read Geography Fellowship.

REFEREED ARTICLES (*including those accepted or in review*)

Halfen, A.F., Johnson, W.C., 2012 (*revisions submitted*). A review of Great Plains dune field chronologies. *Submitted to Aeolian Research*.

Hirmas, D.R., Slocum, T., **Halfen, A.F.**, White, T., Zautner, E., Atchley, P., Liu, H., Johnson, W.C., Egbert, S., McDermott, D., 2012 (*in review*). Effects of seating location and stereoscopic displays on learner outcomes in an introductory physical geography class. *Submitted to Computers and Geoscience*.

Halfen, A.F., Johnson, W.C., Hanson, P.R., Woodburn, T.L., Young, A.R., Ludvigson, G.A., 2012. Activation history of the Hutchinson dunes in east-central Kansas, USA during the past 2200 years. *Aeolian Research* 5: 9–20.

Halfen, A.F., Fredlund, G.G., and Mahan, S.M., 2010. Late-Quaternary Geochronology and Stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. *The Holocene* 20(5): 773–783.

Halfen, A.F., and Hasiotis, S.T., 2010. Traces and Burrowing Behaviors of the Western Harvester Ant Pogonomymrex occidentalis: Paleopedogenic and Paleoecological Significance. *PALAIOS* 25(11–12): 703–720.

Halfen, A.F., and Hasiotis, S.T., 2010. Downward Thinking: Rethinking the "Up" in Soil Bioturbation. In: Gilkes, R.J., and Prakongkep, N. (eds.), *Proceedings of the 19th World Soil Congress; Soil Solutions for a Changing World*. Published on DVD, http://www.iuss.org: pp 21–24.

Hasiotis, S.T., and **Halfen, A.F.**, 2010. The Story of O: The Dominance of Organisms as a Soil-Forming Factor From a Geologic Perspective and Neoichnological Approach. In: Gilkes, R.J., and Prakongkep, N. (eds.), *Proceedings of the 19th World Soil Congress; Soil Solutions for a Changing World*. Published on DVD, http://www.iuss.org: pp 100–103.

BOOK CHAPTERS

Day, M.J., **Halfen, A.F.**, and Chenoweth, S., 2011. Boundary Issues in Assessing Disturbance: The Country, Jamaica. In: Van Baynen, P. (ed.), *Karst Management*, Springer, USA. pp. 399–414.

OTHER PUBLICATIONS

Halfen, A.F., 2010. *Geodiscovery Media Module Questions: Discovering Physical Geography 2nd Edition,* Alan F. Arbogast. John Wiley and Sons Inc., Hoboken, New Jersey USA.

Johnson, W.C. and **Halfen, A.F.**, 2009. Geoarchaeological Investigations in the McCormick Road and Whitside Project Areas—Fort Riley, Kansas. Technical report to the Center for Environmental Management of Military Lands, Colorado State University.

Halfen, A.F., 2009. *Essential Soil Science: A Clear and Concise Introduction to Soil*

Science, Ashman, M.R. and Puri, G., Blackwell, Malden, Massachusetts, USA. Book review for *PALAIOS*, published online.

De Sousa, C. and **Halfen, A.F.** (Eds.) 2008. Challenges to Urban Sustainability Report – Milwaukee, Wisconsin 2008. Report prepared for the Brownfields Research Consortium & Department of Geography Website.

Halfen, A.F., 2008. The state of Milwaukee's Brownfields. In: De Sousa, C. and Halfen, A.F., (Eds.) 2008. Challenges to Urban Sustainability Report – Milwaukee, Wisconsin 2008. Report prepared for the Brownfields Research Consortium & Department of Geography Website.

Halfen, A.F., 2007. Late-Quaternary Geochronology and Stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. University of Wisconsin-Milwaukee, Masters Thesis, pp. 143.

Ronnurud, J. and **Halfen, A.F.** (eds.), 2005. Cheese Factories of Lafayette County, Wisconsin. Willings Print and Design, Darlington, WI. pp. 135.

INVITED PRESENTATIONS *(†=international)*

2011

†**Halfen, A.F.** The past, current, and future of North American Great Plains dune field research: linking chronological data to climate. 18th Congress of the International Union for Quaternary Research, Bern, Switzerland.

Johnson, W.C., **Halfen, A.F.** Chronology of dune activity extracted from the central Great Plains. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Halfen, A.F. Aeolian dune fields of Kansas: a dissertation research overview. University of Kansas, Department of Geography Alumni Advisory Board meeting, Lawrence, Kansas, USA.

2010

Halfen, A.F. The Great Plains' oldest dunes: preliminary results and landscape history of the Robinson Tract. Kansas Biological Survey Colloquium Series. Lawrence, KS, USA.

2007

†Day, M.J., **Halfen, A.F.** Applications of a karst disturbance index: case study - Jamaican Cockpit Country. Windsor Research Center - Cockpit Country Symposium, Windsor, Jamaica.

Halfen, A.F. Holocene geochronology and stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. University of Wisconsin-Milwaukee Department of Geoscience "Soft Rock Series", Milwaukee, WI, USA.

Halfen, A.F. Holocene geochronology and stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. University of Wisconsin-Milwaukee Department of Geography Colloquium Series, Milwaukee, WI, USA.

2006

Halfen, A.F. Late-Quaternary geochronology and stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. University of Arizona Physics Department: AMS Laboratory Colloquium Presentation, Tucson, AZ, USA.

CONTRIBUTED PRESENTATIONS *(†=international)*

2013

Halfen, A.F., S.L. Kozak, Slocum, T.A. Large-screen-format televisions as an alternative 3-D display for teaching introductory physical geography. Association of American Geographers Annual Meeting, Los Angeles, CA, USA.

2012

Halfen, A.F., Johnson, W.C. Spatial and temporal complexities of current Great Plains dune field chronological data. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Lancaster, N., **Halfen, A.F.**, and INQUA Dunes Atlas Project Team. A global digital database and atlas of Quaternary dune fields and sand seas. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Johnson, W.C., **Halfen, A.F.**, McGowen, S. Carter, B., Fine, S., Bement, L.C., Simms, A.R. Last Glacial Maximum development of parna dunes in Panhandle Oklahoma, USA. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

†**Halfen, A.F.**, Johnson, W.C. Does higher resolution OSL sampling lead to better chronological interpretations of aeolian dune fields? 2012 United Kingdom Luminescence and Electron Spin Resonance Meeting, Aberystwyth, Ceredigion, United Kingdom.

†Johnson, W.C., Hanson, P.R., **Halfen, A.F.**, Gaines, E.P. Success in dating late-Pleistocene dunes in central Alaska using a Post-IR IRSL protocol. 2012 United Kingdom Luminescence and Electron Spin Resonance Meeting, Aberystwyth, Ceredigion, United Kingdom.

Halfen, A.F., Hirmas, D.R., Slocum, T., White, T., Zautner, E., Atchley, P., Liu, H., Johnson, W.C., Egbert, S., McDermott, D. A hybrid online/offline curriculum for implementing stereoscopic technology in large lectures. Geological Society of America Annual Meeting, Charlotte, NC, USA. GSA Abstracts with Programs Vol. 44, No. 7.

Halfen, A.F., Johnson, W.C. The current and future state of North American Great Plains aeolian dune fields. Geological Society of America Annual Meeting, Charlotte, NC, USA. GSA Abstracts with Programs Vol. 44, No. 7.

Johnson, W.C., Gaines, E.P., **Halfen, A.F.**, Hanson, P.R., Young, A.R. Role of dune landscape development in determining cultural foci within the Tanana Flats, Central

Alaska. Geological Society of America Annual Meeting, Charlotte, NC, USA. GSA Abstracts with Programs Vol. 44, No. 7.

Woodburn, T.L., Bozarth, S.R., Johnson, W.C., **Halfen, A.F.** Biosilicate reconstruction of the Brady Soil in southwestern Nebraska: the importance of non-short cell phytoliths for paleoclimate interpretations. Geological Society of America Annual Meeting, Charlotte, NC, USA. GSA Abstracts with Programs Vol. 44, No. 7.

Elder, J.A., Miller, B.S., Stevenson, M.F., Vallotto, M., Klipp, B., Johnson, W.C., **Halfen, A.F.** Stratigraphy and chronology of alluvial landforms in the lower Kansas River valley: an undergraduate USGS EDMAP experience. Geological Society of America Annual Meeting, Charlotte, NC, USA. GSA Abstracts with Programs Vol. 44, No. 7.

McDermott, D., Hirmas, D.R., Slocum, **Halfen, A.F.**, T., White, T., Egbert, S., Atchley, P., Johnson, W.C., Gilbreath, A. Do stereoscopic displays improve learning in introductory physical geography classes? AutoCarto International Symposium on Automated Cartography, Columbus, OH, USA.

Fine, S.T., Carter, B.J., McGowen, S.L., Bement, L.C., Johnson, W.C., **Halfen, A.F.**, DeWitt, R., Simms, A.R. Late Pleistocene parna dune formation in the panhandle of Oklahoma. American Quaternary Association Meeting, Duluth, MN, USA.

Gaines, E.P., Johnson, W.C., **Halfen, A.F.** Depositional history of archaeological sites in aeolian dune contexts,
Tanana Flats, Central Alaska. Society for American Archaeology Biennial Meeting, Memphis, TN, USA.

Hasiotis, S.T., **Halfen, A.F.**, Hirmas, D.R. Sediment mixing depths and rates in continental environments and the creation of macrochannels and macropores: lessons learned and implications for alerting porosity and permeability by bioturbation. American Association of Petroleum Geologist International Conference and Exhibition, Long Beach, CA, USA.

Halfen, A.F., Slocum, T.A., White, T., Hirmas, D.R., McDermott, D., Atchley, P., Egbert, S., Johnson, W.C. Assessing the impact of stereoscopic displays in introductory physical geography. Association of American Geographers Annual Meeting, New York, NY, USA.

Slocum, T.A., **Halfen, A.F.**, White, T., Hirmas, D.R., McDermott, D., Atchley, P., Egbert, S., Johnson, W.C., Gilbreath, A. Developing 3-D stereoscopic content for introductory physical geography classes. Association of American Geographers Annual Meeting, New York, NY, USA.

Hirmas, D.R., Slocum, T.A., **Halfen, A.F.**, White, T., Atchley, P., Egbert, S., McDermott, D., Johnson, W.C., Gilbreath, A. Mapping the effects of seating location and stereoscopic displays on learner outcomes in an introductory physical geography class. Association of American Geographers Annual Meeting, New York, NY, USA.

Koop, A.N., **Halfen, A.F.**, Johnson, W.C.. Aeolian sands of Kansas: A new, high resolution database aiding in research throughout the state. Association of American Geographers Annual Meeting, New York, NY, USA.

2011

†**Halfen, A.F.**, Johnson, W.C. Evidence of late-Holocene megadrought activity in dune fields of the United States central Great Plains. Ben-Gurion University of the Negev Minerva Gentner Symposium on Aeolian Processes, Eilat, Israel.

†Johnson, W.C., Mason, J.A., Woodburn, T.L., **Halfen, A.F.** Loess record of pedogenesis during the last glacial–interglacial transition within the central Great Plains. Ben-Gurion University of the Negev Minerva Gentner Symposium on Aeolian Processes, Eilat, Israel.

†**Halfen, A.F.**, Johnson, W.C. Medieval Climatic Anomaly and Little Ice Age dune activity in the Arkansas River Valley, central Great Plains, USA. 18th Congress of the International Union for Quaternary Research Congress, Bern, Switzerland.

Halfen, A.F., Johnson, W.C. Morphology, chronology, and evolution of alluvial terraces within the Kansas River Valley, Kansas, USA. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Johnson, W.C., **Halfen, A.F.** Chronology of dune activity extracted from the central Great Plains. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Halfen, A.F. LiDAR analysis of channel morphology and associated landforms of the lower Wisconsin River, Sauk County, Wisconsin. Geological Society of America Annual Meeting, Minneapolis, MN, USA.

Halfen, A.F., Hasiotis, S.T. Soil mixing rates of the Western Harvester Ant: a neoichnological perspective on the importance of the ant in the paleopedological record. Geological Society of America Annual Meeting, Minneapolis, MN, USA.

†Slocum, T., **Halfen, A.F.**, White, T., Hirmas, D., Egbert, S., McDermott, D., Johnson, W.C. Adoption of stereoscopic displays in geographic education: a persistent problem in geographic visualization. International Cartographic Association's GeoVisualization Commission, Paris, France.

Johnson, W.C., **Halfen, A.F.,** Spencer, J.Q.G., Hanson, P.R., Young, A.R. Aeolian sand evidence for landscape instability in the central Great Plains during MIS 3. Geological Society of America Annual Meeting, Minneapolis, MN, USA.

Creason, G.C., Hekman, M.S., Vallotto, M., **Halfen, A.F.**, Johnson, W.C. Valley-fill architecture and alluvial landforms within the upper Kansas River: an undergraduate USGS EDMAP experience. Geological Society of America Annual Meeting, Minneapolis, MN, USA.

Fine, S.T., McGowen, S.L., Carter, B.J., Bement, L.C., Johnson, W.C., Simms, A.R., **Halfen, A.F.** Investigation of a parna (Silt) Dune formation in the panhandle of Oklahoma. Soil Science Society of America International Conference, San Antonio, TX, USA.

Halfen, A.F., Johnson, W.C., Hanson, P.R., Spencer, J.Q.G., Woodburn, T.L., Young, A.R. Rapid climate shifts, dune activity, and megadroughts in the central Great Plains around the Medieval Climatic Anomaly and Little Ice Age. Association of American Geographers Annual Meeting, Seattle, WA, USA.

Johnson, W.C., Mason, J.A., Woodburn, T.L., **Halfen, A.F.**, Hasiotis, S.T., Moore, R. The Pleistocene–Holocene transition in the central Great Plains: an unashamed lust for loess. Association of American Geographers Annual Meeting, Seattle, WA, USA. (*presented by **A.F. Halfen***)

2010

Halfen, A.F., Johnson, W.C., Hanson, P.R., Spencer, J.Q.G., Woodburn, T.L., Young, A.R. A new high-resolution chronology of megadrought following the Medieval Climatic Anomaly and the Little Ice Age in the central Great Plains, USA. American Geophysical Union Fall Meeting, San Francisco, CA, USA.

Halfen, A.F., Johnson, W.C., Hanson, P.R., Spencer, J.Q.G., Young, A.R. The Great Plains' oldest sand dunes. Association of American Geographers Great Plains-Rocky Mountains Regional Meeting, Lawrence, KS, USA.

Johnson, W.C., **Halfen, A.F.**, McGowen, S., Carter, B.J., Bement, L.C. Silt dunes of panhandle Oklahoma. Association of American Geographers Great Plains-Rocky Mountains Regional Meeting, Lawrence, KS, USA.

Halfen, A.F., Johnson, W.C., Hanson, P.R., Woodburn, T.L., Young, A.R. New ages of dune activity during and following the Medieval Climatic Anomaly on the eastern margin of the Great Plains. Geological Society of America Annual Meeting, Denver, CO, USA.

Halfen, A.F., Johnson, W.C., Hanson, P.R., Spencer, J.Q.G., Young, A.R. Geomorphology and activation chronology of the Arkansas River dune field. Geological Society of America Annual Meeting, Denver, CO, USA.

Rockel, R.A., Wooten, S.M., Sanderson, B.F., **Halfen, A.F.**, Johnson, W.C. Geological mapping and stratigraphic characterization of alluvial landforms within the lower Kansas River valley: an undergraduate USGS EDMAP experience. Geological Society of America Annual Meeting, Denver, CO, USA.

†**Halfen, A.F.**, Hasiotis, S.T. Downward thinking: rethinking the "up" in soil bioturbation. 19th World Soil Congress, Brisbane, QLD, Australia.

†Hasiotis, S.T., **Halfen, A.F.** The story of O: the dominance of organisms as a soil-forming factor from a geologic perspective and neoichnological approach. 19th World Soil Congress, Brisbane, QLD, Australia.

Hasiotis, S.T., **Halfen, A.F.** Biota as a major Ssoil-forming factor and ecosystem engineers through recent earth history based on continental trace fossils: soil biota as geoengineers. Geological Society of American Rocky Mountain Meeting, Rapid City, SD, USA.

Halfen, A.F., Hasiotis, S.T. New Insights of Soil Bioturbation by the ant and other soil-dwelling organisms: modern and paleopedologic significance. American Association of Petroleum Geologist International Conference and Exhibition, New Orleans, LA, USA.

2009

[†]Day, M.J., **Halfen, A.F.** Boundaries and disturbance in the Cockpit Country, Jamaica. International Cave Conference: U-Cave in Danyang, Danyang-gun, Chungcheongbuk-do, Korea.

Halfen, A.F., Hasiotis, S.T. Significance of the Western Harvester Ant in soil bioturbation and pedological development: results of neoichnology experiments (*new data presented*). Soil Science Society of America International Conference, Pittsburgh, PA, USA.

Halfen, A.F., Spencer, J.Q.G., Johnson, W.C., Hanson, P.R., Young, A.R. Luminescence ages for dune activation on a Pleistocene terrace of the Kansas River valley. Geological Society of America Annual Meeting, Portland, OR, USA.

Halfen, A.F., Hasiotis, S.T. Significance of the Western Harvester Ant in soil bioturbation and pedological development: results of neoichnology experiments. Geological Society of America Annual Meeting, Portland, OR, USA.

Johnson, W.C., Hanson, P.R., **Halfen, A.F.**, Woodburn, T., Young, A.R. Late Holocene dune activation after the Medieval Climatic Anomaly in the Arkansas River Valley, south-central Kansas. Geological Society of America Annual Meeting, Portland, OR, USA.

Halfen, A.F., Hasiotis, S.T. Traces and burrowing behaviors of the Western Harvester Ant *Pogonomymrex occidentalis*: paleopedogenic and paleoecological significance. American Association of Petroleum Geologist International Conference and Exhibition, Denver, CO, USA.

2008

Halfen, A.F., Fredlund, G.G., Mayer, J.A., Holliday, V.T. Inferring vegetation and climate from playa phytoltih assemblages. Geological Society of America Annual Meeting, Houston, TX, USA.

2007

Halfen, A.F., Fredlund, G.G., Mahan, S.A. Holocene Geochronology and Stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. Geological Society of America Annual Meeting, Denver, CO, USA.

2006

Halfen, A.F., Fredlund, G.G., Mahan, S.A. Late Quaternary Geochronology and Stratigraphy of the Casper Dune Field, Casper, Wyoming, USA. Geological Society of America Annual Meeting, Philadelphia, PA, USA.

COMPETITIVE FUNDING

In Review:	National Science Foundation, Frontiers in Earth Systems Dynamics (FESD 12-547): Aeolian dune systems in space and time. (PIs: *N. Lancaster, L. Scuderi, R. Ewing, A.F. Halfen, P. Avouac, C. Newman, M. Richardson, D. Pennington, G. Weissman, and A. Ellwein*) Decision date: 12/31/12.
2011	University of Kansas, Doctoral Student Research Fund: funding to support research on aeolian dunes of the Kansas River valley, KS, USA. $1,500. (PI: *A.F. Halfen*)
08/10 – 02/12	National Science Foundation, Doctoral Dissertation Research Improvement Grant (NSF-DDIG): Holocene megadroughts of the Central Great Plains (BCS/SBE-1030254). $11,970. (PIs: *A.F. Halfen and W.C. Johnson*)
2010	Geological Society of America Research Grant: funding to support research on aeolian dunes in the Arkansas River valley, KS, USA. $3,402. (PI: *A.F. Halfen*)
2010	American Philosophical Society, Lewis and Clark Fund for Exploration and Field Research: funding to support research on aeolian dunes in the Arkansas River valley, KS, USA. $2,000. (PI: *A.F. Halfen*)
2007	United States Geological Survey research support: funding for 12 optically stimulated luminescence ages. $12,000. (PI: *A.F. Halfen*)
2007	University of Arizona National Science Foundation AMS Laboratory research support: funding for 20 radiocarbon ages. $12,000. (PI: *A.F. Halfen*)
2007	Geological Society of America Research Grant: funding to support research on aeolian dunes in Casper Wyoming. $2,000. (PI: *A.F. Halfen*)
2007	University of Wisconsin-Milwaukee Mary Jo Read Field Research Grant: funding to support research on aeolian dunes in Casper Wyoming. $1,700. (PI: *A.F. Halfen*)

ADDITIONAL FUNDING

Composite institutional funding (research and conferences):	$8,175
Composite organizational funding (research and conference):	$2,375

TEACHING EXPERIENCE

Course	Title	Time
GEOG 104	Principles of Physical Geography	Fa 2008 – 2011, Sp 2010 – 2011, Sm 2011–2012
ATMO 105	Introductory Meteorology (Lab)	Sp 2009
GEOG 2950	Process Geomorphology	Wn 2008
GEOG 1700	Physical Geography: An Introduction	Sp 2008
GEOG 475	Geography of Soils	Fa 2006–2007
GEOG 120	Our Physical Environment	Fa 2005–2007, Sp 2006–2008

Regular Guest Lecture: GEOL 729 - Ichnology, Fa 2011, 2012
GEOL 791 - Ichnobiogeoscience, Sp 2010, 2011

WORKSHOP/PANEL PARTICIPATION

Panelist, University of Kansas Graduate Studies: National Science Foundation Doctoral Dissertation Improvement Grants Workshop, September 30, 2011.

Panelist, American Geological Institute and United States Geological Survey cosponsored GeoConnection Webinar discussion on the USGS Educational Mapping Program, September 21, 2010.

PROFESSIONAL SERVICE

Member, Geological Society of America Annual Program Committee 07/11 – Present

UNIVERSITY SERVICE

KU Geography graduate student representative to the faculty	08/10 – 01/12
KU graduate student representative on the colloquium committee	08/08 – 01/12
KU Geography physical geography laboratory coordinator	08/10 – 08/11
KU Geography new student orientation	08/10
UW-Milwaukee graduate student representative to the faculty	08/07 – 05/08
UW-Milwaukee Department of Geography Colloquium Committee	08/06 – 01/08
UW-Milwaukee New Teaching Assistant Orientation	08/07

PROFESSIONAL AFFILIATIONS

American Association for the Advancement of Science	2012 – Present
American Association of Geographers (AAG)	2005 – Present
American Association of Petroleum Geologist (AAPG)	2009 – Present
American Geophysical Union (AGU)	2009 – Present
Geological Society of America (GSA)	2005 – Present
International Society for Aeolian Research (ISAR)	2008 – Present
Charter Member (Journal of Aeolian Research)	
Soil Science Society of America (SSSA)	2009 – Present

Society for Sedimentary Geology (SEPM) 2009 – Present